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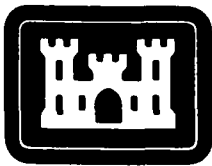
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EVALUATION OF QUALITY AND PERFORMANCE OF STONE AS RIPRAP OR ARM--ETC(U)
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EVALUATION OF QUALITY AND PERFORMANCE OF STONE AS RIPRAP OR ARMOR

by

Richard J. Lutton, Billy J. Houston, James B. Warriner

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September 1981

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number) The durability and size gradation of the rock materials are important aspects of construction of slope protection and dikes, jetties, and breakwaters. Some rocks are intrinsically susceptible to deterioration during service, while others are affected adversely by excessively close jointing in the source quarry. Elsewhere problems may arise from deficiencies in quarrying, processing, and handling, and in placement techniques. All 36 Corps of Engineers Districts in the continental United States and two operational		

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20. ABSTRACT (Continued).

Divisions have responded to requests for summaries and specific information on their experiences within the past 10 years. These data and observations made during field visits reveal causes of some problems and suggest some improvements; e.g., quarry examinations should be made in considerable detail, and representative samples for testing might be obtained from all major rock varieties.

Although problems with stone quality and performance are so infrequent and minor that they are considered insignificant in about 80 percent of the Corps of Engineers offices, it is evident that an even further reduction in problems Corps-wide is attainable on future projects. Advances in the state of the technology will come both in laboratory testing and in the area of responsibility of the District geotechnical staff.

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PREFACE

The study reported herein was performed by personnel of the Geotechnical Laboratory (GL) and Structures Laboratory (SL) of the U. S. Army Engineer Waterways Experiment Station (WES). The investigation was sponsored by the Office, Chief of Engineers, U. S. Army, under CWIS Work Unit 31621, "Rock Research Program" of the Civil Works Investigation Study on Materials.

The report was prepared in sections by Dr. R. J. Lutton, GL, Mr. B. J. Houston, SL, and Mr. J. B. Warriner, GL. Dr. Lutton wrote Parts I, II, VI, and VII and assembled Part IV. Mr. Houston wrote Part III and Appendices A and B. Mr. Warriner wrote Part V. The experimental laboratory testing for Appendix A was conducted by Messrs. J. C. Tom and G. S. Wong, SL. Generalizations and details of project experience contributed by 38 Corps of Engineers offices constitute a major part of this report for which the authors are grateful. General supervision was provided by Dr. D. C. Banks, Acting Chief of GL, and Mr. Bryant Mather, Chief of SL.

COL Nelson P. Conover, CE, and COL Tilford C. Creel were Commanders and Directors of the WES during the preparation of the report. Mr. Fred R. Brown was the Technical Director.

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CONVERSION FACTORS, U. S. CUSTOMARY TO METRIC (SI)
UNITS OF MEASUREMENT

U. S. customary units of measurement used in this report can be converted to metric (SI) units as follows:

<u>Multiply</u>	<u>By</u>	<u>To Obtain</u>
Fahrenheit degrees	5/9	Celsius degrees or Kelvins*
feet	0.3048	metres
inches	25.4	millimetres
miles (U. S. statute)	1.609344	kilometres
pounds (mass)	0.4535924	kilograms
pounds (mass) per cubic foot	16.01846	kilograms per cubic metre
tons (2000 lb, mass)	907.1847	kilograms

* To obtain Celsius (C) temperature readings from Fahrenheit (F) readings, use the following formula: $C = (5/9)(F - 32)$. To obtain Kelvin (K) readings, use: $K = (5/9)(F - 32) + 273.15$.

EVALUATION OF QUALITY AND PERFORMANCE OF STONE AS RIPRAP OR ARMOR

PART I: INTRODUCTION

1. Often the most cost-effective form of slope or dike protection in areas where suitable rock is plentiful is a blanket of riprap or armor; most likely such engineering features will remain foremost in the foreseeable future. As procedures for designing protection against current and wave action have become more sophisticated and effective, the importance of the durability and size gradation of the material has become relatively even more critical.

Purpose of Study

2. The purposes of this study are to identify problems associated with the use of stone as slope protection and armor, and to delimit the magnitude of such problems Corps-wide. It has also been the intention in this study to describe, as appropriate, any apparent ways for achieving improvements in selection and placement and, otherwise, to identify subject areas where further research would be productive.

Scope of Report

3. Part II of this report categorizes the general types of stone problems from a materials standpoint and from construction standpoints. Numerous visits to projects have provided opportunities to examine deterioration in place; descriptions of other deterioration phenomena have been taken from the literature. Part III reviews the existing laboratory tests and also includes comments on limitations and applicability to evaluation of large stone. The general Corps of Engineers (CE) experience found in Part IV forms a major part of this study. The viewpoints expressed by the Districts and Divisions are diverse, but when combined and considered in detail, the responses in

Part IV form a thorough review of the current state of the technology of evaluation, engineering, and construction for slope protection and armor. Certain generalizations from Corps-wide experience have been made in Parts V and VI concerning basic problems, important factors, best geological types, and preferred procedures. These generalizations also impact on study conclusions in Part VII. Finally, in Part VII, those subject areas where future studies seem to be needed are identified and distinguished as to whether they involve laboratory testing or are of a geotechnical nature.

Previous Studies

4. An extensive review was made in 1946 on embankment slope protection with input from CE Districts (U. S. Army Engineer Districts, Portland, 1946; Sacramento, 1947; Pittsburgh, 1946; Cincinnati, 1946; San Francisco, 1946; and Galveston, 1946). In that review, the Office, Chief of Engineers (OCE), requested and received information from Districts on various types of slope protection for earth dams. The Districts' reports presented a picture of the relative effectiveness or deficiencies of various slope surface treatments (principally vegetation and riprap) with relation to permanence, durability of materials, construction and maintenance, as well as local and regional considerations in their use. The emphasis of the 1946 study was on slope protection for earth dams only, but some experience gained from construction and maintenance of streambank and levee slope protection was believed to be pertinent and was included. Other useful CE investigations during the same period were focused specifically on streambank protection (e.g., U. S. Army Engineer Districts, Baltimore, 1949, and Seattle, 1950).

5. Other reviews of more localized scope than the OCE study have been undertaken. In 1964, the U. S. Army Engineer Division, Missouri River, requested evaluations of freeboard and slope protection from its Districts (U. S. Army Engineer Districts, Kansas City, 1964; and Omaha, 1965, 1967). Although the emphasis was on evaluating riprap design criteria, an appreciation of the importance of rock characteristics is implicit in these evaluations also, particularly in the reply

from Kansas City (U. S. Army Engineer District, Kansas City, 1964). In 1977, the U. S. Army Coastal Engineering Research Center canvassed certain Districts for experience on quality of rock in coastal structures. The results of this review have not yet been reported.

6. Independent efforts by the U. S. Department of Interior Bureau of Reclamation on riprap for embankment dams were also of importance and serve as valuable background to the present study. The Bureau published two reports (Esmiol 1968 and Davis 1973): one summarizes 149 projects, and the other is a review of practices and procedures.

7. Some of the slope protection projects reviewed in previously cited studies were fairly old, and some of the current procedures, particularly the inclusion of a filter layer, were not utilized at the time of their construction. The Districts' responses to the 1946 inquiry from the OCE were collated into a summary of nationwide experience (U. S. Army Engineer Waterways Experiment Station 1949a), but even individual descriptions are valuable in revealing virtually the full range of problems experienced. Cases of rock deterioration, use of unsuitable rock, deficient design (according to present standards), and poor construction were interspersed among the generally satisfactory projects. These descriptions from 35 years ago are still useful since similar problems have continued to appear occasionally to the present.

Design and Construction

8. Rock slope protection as treated in this report is intended to resist two separate water actions: channel flow and wave attack. Entirely distinct designs are necessary for these separate environments.

Channel slope design

9. The resistance of stone to displacement by flowing water depends primarily upon the weight of individual stones. To specify the appropriate weight of individual stones, the designer must first determine the size of channel existing or required for the design discharge, then calculate the design discharge velocity, and finally, select the stone size using appropriate charts or standard equations.

Factors are available for increasing design stone size to withstand increased velocities at channel curves. The appropriate references on design are Department of the Army, Office, Chief of Engineers (OCE) (1970, 1971a) and U. S. Army Engineer Waterways Experiment Station (1970).

Shore protection design

10. Several procedures, again using charts, are available for designing the stone size sufficient to resist disturbance by the design wave action (Dept. of the Army, OCE, 1963, 1971b, 1978 and U. S. Army Coastal Engineering Research Center 1977). Additional uncertainty is introduced by the availability of more than one way of estimating the height of the design wave. Wave height can be estimated from the wind fetch, or it can be based on a long record of actual measurements. Usually the severity of the wave attack and the availability and cost of material dictate the type and extent of slope protection. Stone usually provides the most suitable protection. Conspicuous exceptions are the very large stones that are not available in required quantities; dolos or other shaped concrete units are constructed instead.

Stone placement

11. Two basic methods of construction are practiced, placed stone and dumped stone. Placed stone layers require less material than dumped stone layers and are sometimes used where the cost of stone is exceptionally high. Placed construction is generally restricted today to larger size stone and includes both manual and machine placement. Manually placed stone with a degree of keying or fitting among stones (paragraph 36) is somewhat more regular and finished in appearance than other types of slope protection, but some experience indicates that performance may be less satisfactory (Dept. of Commerce, Bureau of Public Roads 1965). Pell-mell placement of stone is more random and gives a rougher surface that may be preferable for dissipating wave energy.

12. A dumped stone blanket is the most flexible and is often preferred in present practice. Dumped stone readily adjusts to uneven settlement and also has any advantages associated with rough surfaces.

In areas where stone is plentiful, dumped stone is generally the least costly type of placement and design and may enjoy an advantage where safety is not a factor, i.e., where the consequences of any conceivable failure of the slope protection will not threaten human well-being.

13. All types of placed stone protection should be laid on a bedding of gravel or crushed stone unless the gradation of the next lower zone (or natural soil) is such that it will not migrate up through the stone blanket. The design of bedding parallels the design of soil filters, which is discussed in texts on soil mechanics and in publications by the Department of the Army, OCE (1971a, b).

PART II: DESCRIPTION OF PROBLEMS

14. It is possible to describe pertinent stone riprap and armor problems under three headings: deterioration phenomenology, specification deficiencies, and material life. From the descriptions which follow it should be possible for the reader to anticipate most deterioration that may take place, how soon it can develop, and the effects that such deterioration and other shortcomings have on the achievement of design function.

Deterioration Phenomenology

15. The deterioration of the component blocks of riprap and armor stone may be categorized into a relatively few phenomena as described below.

Cracking

16. The cracking phenomenon is characterized by the development within individual rock fragments of one or a few throughgoing cracks. Where a geological fabric (such as bedding) is present in the fragments, the cracks usually propagate parallel or perpendicular to planar geological structures. In those stones where well-healed joints occur, it is common to find the cracking along these potentially weak surfaces. This observation suggests an obvious guide for avoiding the cracking of riprap; select sources that are relatively free of even well-healed joints below the scale of individual rock blocks.

17. An important case-in-point of cracking is the experience with limestone and dolomite armor stone on dikes designed and constructed to retain spoil dredged from harbors on the Great Lakes. Designs to resist wave action called for blocks on the cap and lakeside slope commonly as large as 10 tons.* The problem of cracking recurred frequently in the course of construction between 1968 and 1975 among the numerous projects.

* A table of factors for converting U. S. customary units of measurement to metric (SI) units is given on page 4.

The dikes were largely uninspected during the winter months of inactivity. Upon resumption of construction activity in the spring, inspectors commonly found numerous cracked stones.

18. The armor stone is limestone, dolomitic limestone, and dolomite from several quarry sources in the region. Bedding partings and stylolites in the quarries are developed to such a common extent that blocks seldom exceed 5 ft perpendicular to bedding. For the same reason, stones are somewhat blocky in shape, with other surfaces commonly oriented perpendicular to bedding. Some surfaces perpendicular to bedding are parallel in cases where a joint set is evident.

19. Figure 1 illustrates the arrangement of cracks in a representative block. It was common to find that bedding, though visually faint, was sufficient to establish influential anisotropy. By far most cracks either followed parallel or crossed perpendicular to bedding. Cracking in no way could be dismissed as spalling of corners or pervasive disintegration. Instead, the cracks were clean, simple, and few; in some cases, the blocks were divided in half.



Figure 1. Cracking of armor stone on dike in Lake Michigan (note pencil at left)

20. Where cracked blocks were numerous on the dike, they potentially compromised the armor design by greatly reducing the median (percent weight) block size. On the other hand, most of the cracks observed during this study (i.e., within a few years after placement) had not resulted in complete separations. The parts of the cracked stones usually remained together, wedged in place, or still partially joined.

Spalling

21. Spalling describes the special process of deterioration in which relatively thin shells break away from the fragment surface. Corners and edges of fragments are particularly vulnerable so that the rock fragment evolves toward a rounded form. The whole process is observationally analogous to spalling of small, dried pieces of some shale or clay-rich rock upon immersion in water. Frequently this small-scale treatment will result in a rapid exfoliation of shells of material. The analogy may be directly applicable to inferior, clay-rich riprap stone. However, the analogy cannot be carried very far before one encounters the problem of the occurrence of the spalling phenomenon in rock containing little or no clay minerals. Establishment of a generalized mechanism and origin of such spalling apparently must await further study.

22. Figure 2 shows an example of spalling of basalt at Wickiup Reservoir, Oregon (Esmiol 1968). In this particular instance, the spalling had been observed to occur as a result of fishermen building fires on the riprap slope. Fires built in the winter for warmth thermally stressed adjacent riprap fragments and caused spalling. This particular cause is not as unique and insignificant as might first appear since it is locally common practice to burn logs, other drift, and vegetation that accumulate on the slopes seasonally.

23. More widespread and serious spalling deterioration is associated with sedimentary rocks containing appreciable clay minerals. The expansion-contraction process upon periodic wetting and drying presumably is responsible. It is suffice to say that the inferiority of marl, mudstone, and shale for slope protection is widely recognized and



Figure 2. Spalling of basalt at Wickiup Lake

seldom if ever experienced in the CE today. Commonly the spalling passes gradationally into even more serious, general disaggregation (paragraph 27) or disintegration (see paragraph 29) behavior. These advanced deterioration phenonema are discussed further below.

Delaminating or splitting

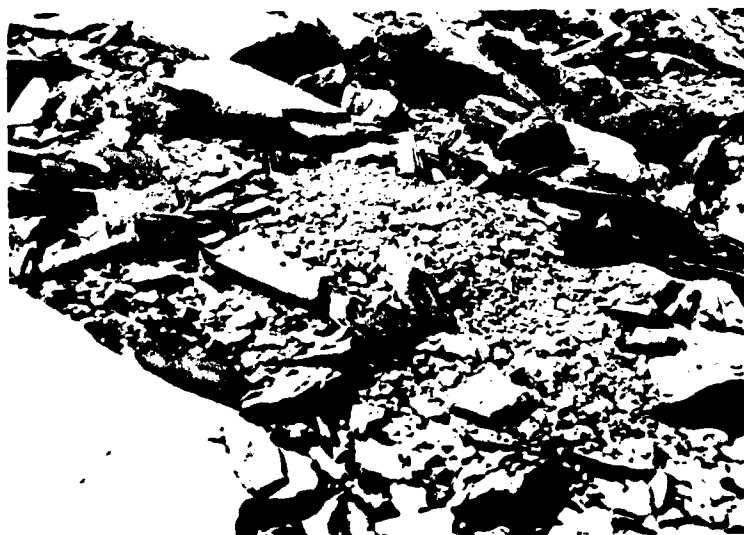
24. Certain rock materials are prone to delaminating, slabbing, or splitting because of inherent geological structure. Many bedded sedimentary rocks and a few layered volcanic or metamorphic rocks separate preferentially along these geological features regardless of the cause of deterioration. This potential problem is widely recognized and most specifications for riprap and armor stone prohibit the inclusion of rocks containing prominent bedding, shaly layers, partings, stylolites, etc. In many cases, such materials are unavoidable within the constraints of costs or time schedule, and as a result, delaminating or splitting is among the most common forms of rock breakdown.

25. Figures 3 and 4 show examples of in-service delaminating and splitting, respectively. Figure 3 illustrates an extreme example from Lawrenceburg, Indiana, in which 80 percent of the levee riprap was in various stages of partial to complete disintegration (U. S. Army Engineer District, Cincinnati, 1946). Eighteen inches of riprap was specified to have maximum and minimum dimensions of 24 and 4 in. The rock was described as a somewhat weathered arenaceous limestone, extremely thin bedded and shaly. The disintegration caused the thickness of the riprap in some places to decrease 10 to 20 in. and produce low spots. The deteriorated condition had been reached after 5 years, and it was estimated that in 5 more years (total of 10 years) all riprap slopes at Lawrenceburg would have to be replaced if there were any periods of high water that would wash out the disintegrated rock. As far as meeting the design, this riprap had already failed.

26. Figure 4 shows the slabbing or splitting phenomenon as it commonly develops in volcanic rock. A subtle distinction from delaminating can be made on the basis of the characteristic separation along one or a few cracks, with intervening rock remaining intact subsequently. In delaminating subsidiary cracks are numerous. The particular example



a. Condition as originally constructed in 1940



b. Condition in 1946 after deterioration

Figure 3. Delaminating of limestone at
Lawrenceburg on Ohio River



Figure 4. Slabbing of rhyolite at Jackson Lake

is from a revetment at Jackson Lake, Wyoming, where the rock has been described as a rhyolite of characteristically low unit weight (U. S. Army Engineer District, Portland, 1946). Inspection in 1946 revealed considerable damage from drift logs driven by wind and wave action against the riprap. This damage was of no consequence to material performance. The inspection did find, however, a general deterioration of material caused by a tendency of some of the rhyolite to split into thin slabs. It should be understood, of course, that this slope was placed in 1915 and 1916, and 30 years of service had already accrued in this severe environment.

Disaggregating

27. Disaggregating can be a particularly severe problem when it occurs in riprap. Disaggregating appears to be more likely to occur in granular rather than crystalline rocks. In granular or clastic

sedimentary rock individual grains are sometimes held together only by a relatively weak cementing material. This characteristic is in distinction from crystalline rocks where the intergrowth of component grains provides a strengthening mechanical interlock. Disaggregation is manifested by a continuing erosion, abrasion, or flaking away of increments of rock (near grain-size) leading to fragment rounding and reduction in size. The case below illustrates the usual association of this behavior with relatively young geological formations that have not yet undergone much induration or metamorphism.

28. A good illustration of disaggregating comes from another relatively old case. Figure 5 shows conglomerate used for upstream slope protection at Eagle Mountain Dam, Texas (U. S. Army Engineer District, Galveston, 1946). Hard, dense, sound fossil shells form most of this Lower Cretaceous conglomerate. Two varieties of the conglomerate may be distinguished. The matrix of one is dark and shaly and the other type has very little matrix as such, the conglomerated whole shells being bound together with small shell fragments tightly cemented with calcareous binder. The shaly conglomerate generally weathered to a much more marked degree than did the conglomerate with the calcareous matrix, although many pieces of shaly conglomerate remained intact and many pieces of the other type weathered badly. Where the shaly conglomerate weathered, it formed large quantities of loose shells that filled in and in some cases almost leveled off the interstices between the unweathered or partly weathered blocks.

Disintegrating

29. The process characterized as disintegrating is conveniently reserved in this report for application to cases of notably severe and rapid deterioration. Individual pieces shown in Figures 3b and 5 have obviously disintegrated leaving few or no traces of the original fragments and making serious, though localized, deficiencies in the slope protection. Use of inferior rock susceptible to disintegrating is rare today and then usually involves only small fractions included with satisfactory rock during the quarrying operation. It is sometimes unavoidable that a shaly parting or zone of weathered rock associated

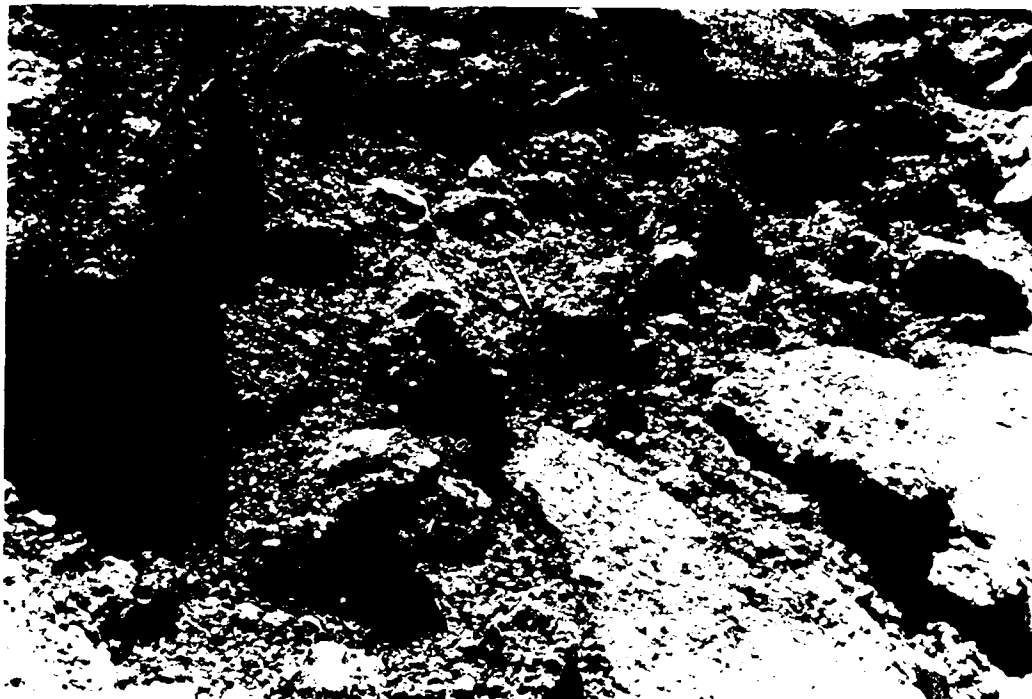


Figure 5. Disaggregating of conglomerate at Eagle Mountain Lake

with a joint crosses a quarry face and must be taken with the acceptable rock. There are, of course, sharp limitations to how much of this contamination is tolerable, and this judgment weighs heavily on the inspection staff.

Dissolving

30. Under certain unusual conditions such as emergencies, it has been necessary to use inferior rocks that were immediately available for temporary slope protection. A local rock containing relatively soluble anhydrite was used to protect the abutment of the Hazard Perry Bridge, when it was threatened in the 1973 flood of the Red River in Louisiana. In 1979, after 6 years in place, the stone had been substantially reduced in size by weathering (Figure 6). The weathering mechanism apparently combined hydration of the anhydrite to gypsum as well as overall dissolution of the rock.

31. Gypsum occurs as a minor constituent of some of the Silurian/Devonian limestones and dolomites around Lake Erie. In testing and examining the rock from one quarry near Niagara Falls, the Ohio River Division Laboratory has called attention to the presence of gypsum as nodules in the samples. It was suggested that there existed a potential for solution of the gypsum and possible deterioration of the stone in service as riprap since considerable solution occurred during freeze-thaw testing.

Construction and Specification Deficiencies

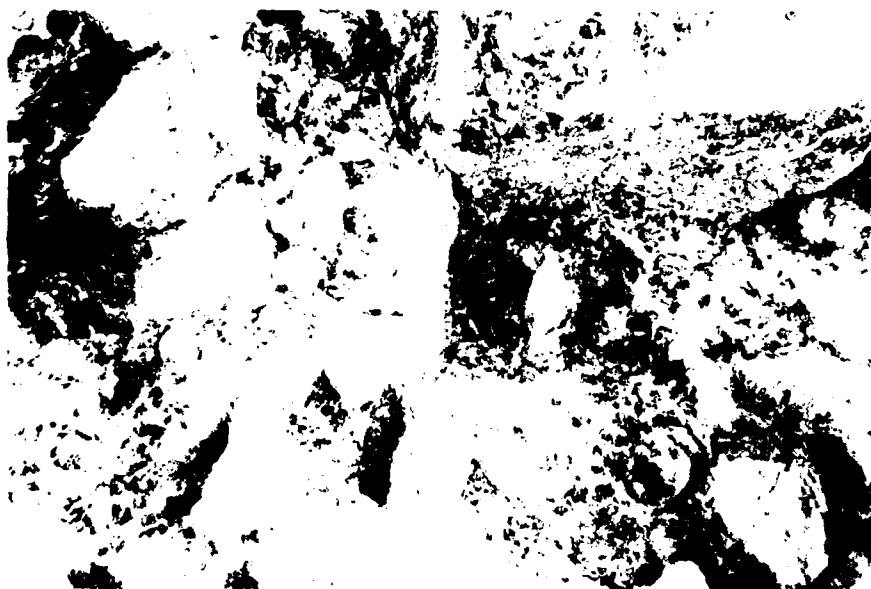
32. Certain characteristics of riprap as a material are distinct and apart from intrinsic properties of the intact pieces, e.g., block size, gradation, and shape. Problems can arise involving these characteristics from certain quarrying procedures and to a lesser extent from handling and placement procedures.

Average stone size

33. The average weight of the stone is the primary factor in design as noted in paragraphs 9 and 10. Materials that are approved, listed, or otherwise suggested for use as riprap sometimes fail to



- a. Approximately half of the original pieces have been reduced in size by weathering while there is less effect on the larger pieces; they do have solution channels developing along incipient cracks



- b. The most pronounced degradation from weathering was concentrated at the tops of the pieces

Figure 6. Riprap at Hazard Perry site

achieve specified average dimensions and weight in production (quarrying, transportation, and placement). The most likely causes of this problem are as follows:

- a. Overlooking the limitations in stone size imposed by closely spaced joints in the quarry.
- b. Excessive blasting patterns that are concentrated on excavation volumes rather than on material quality.
- c. Subtle geological processes causing changes in the stone after excavation (i.e., weathering, stress relief, and other forms of durability problems manifested as above).
- d. Poor inspection procedures.

Stone gradation

34. The size distribution (gradation or range) around the average size is another factor of design that is specified. Deficiencies can arise during construction by a failure of the contractor to supply the gradation as specified. Again, the most common causes of this deficiency are inherent limitations in the gradation imposed by geological features and problems introduced by the particular blasting methods. In addition, the contractor or the quarry operator may be ineffective or lax in screening or blending to achieve the appropriate gradation.

35. Of course, any major material deterioration after construction will change the gradation also. Where deterioration is widespread or of considerable magnitude, fine sizes increase and large sizes decrease, and the gradation as well as average size of stone may fall short of design.

Keying

36. Keying refers to the fitting together of adjacent rocks to a sufficient degree to provide an increment of stability (Figure 7). Keying is important and desirable in many manually placed stone blankets. Such riprap does not depend on a gradation of sizes to reduce void space but instead depends on keying.

37. The potential success of keying can be addressed from a source evaluation point of view by considering the geological structures that will be encountered in the quarry. Bedding partings and fairly regular



Figure 7. Close fitting or keying of riprap on levee at Williamsport, Pennsylvania, circa 1941. Such hand placement is often too costly today

joint sets tend to produce blocky stones that will facilitate keying. For example, the somewhat blocky stone shape produced by lava flow structure appears to be one of the attributes of the 10- to 20-ton basalt blocks produced at the Fisher quarry, Washington. In jetty construction and renovation along the Oregon coast the crane operator is able to place individual basalt stones with long dimensions inclined downward in the dikeward direction about 20 deg from horizontal. Irregularities among blocks and the overall stairstep stacking (i.e. keying) provide roughness to the jetty's exposed surface for dissipating wave energy.

Stone shape

38. Quarries with irregular jointing and little or no bedding are usually suited for producing dumped rock riprap. Besides having irregular stone shapes these quarries usually produce well-graded material that can be processed to meet specifications.

39. To help minimize instability from wave action and channel

flow, specifications often require that the individual blocks in riprap and armor not exceed a length-to-width ratio of 3. Problems in achieving this requirement can only develop in the following ways:

- a. Acceptance of unsuitable rock at the job site.
- b. Subsequent deterioration of the rock in place, mostly by splitting.

The problem can be minimized by care in handling and preliminary evaluation of the quarry source to spot geological features that will tend to produce slabby rock. It may also be possible to adjust blasting patterns to reduce slabiness, although this adjustment frequently leads to an overall reduction in fragment size.

Material Life

40. The last aspect of problem description concerns the material life. It is important to know whether the protection stone will remain functional for a relatively long period of time or, in the other extreme, fail within 1 year of placement. In many riprap deterioration problems most of the cracking, delaminating, and disintegrating takes place in the first few years. Disaggregating is often a more extended process depending partly on accumulation of abrasive actions in some cases.

41. Where a rapid deterioration is noted, it must be speculated that the riprap failure is reached early in riprap stone life and its full benefits are not to be realized. The cost-benefit ratio is therefore unfavorably high. In other words, some riprap that may not be replaced until 10 years after initial placement probably has failed according to design within 1 or 2 years. This whole concept of material or performance life of riprap appears to deserve careful review. Perhaps some sort of factor of safety rationale is needed for evaluating the condition of riprap in service for a period of time.

PART III: LABORATORY TESTING

42. Tests conducted to evaluate riprap and armor stone may vary from District to District in the CE. Variations are to be expected and are probably desirable considering the differing types of stone and exposure conditions within the 50 states. Guide specifications covering stone protection give much latitude to the Districts in the tests conducted and their interpretation for acceptance or rejection of the stone.

Guide Specifications

43. Corps of Engineers Guide Specifications CE-1308, "Civil Works Construction, Stone Protections (Slopes and Channels)," July 1958, and Amendments 1 and 2 specify as follows in regards to MATERIAL:

- a. General. All stone for the protection work shall be durable stone as approved by the Contracting Officer. The sources from which the Contractor proposes to obtain the material shall be selected well in advance of the time when the material will be required in the work. *(Selected stone from the required excavation may be used if satisfying all requirements as to quality and dimensions.) Suitable samples of stone protection material shall be submitted to the Contracting Officer for approval prior to delivery of any such material to the site of the work. Unless otherwise specified, all test samples shall be obtained by the Contractor and delivered at his expense to a point designated by the Contracting Officer at least 60 days in advance of the time when the placing of the stone protection is expected to begin.
- b. Quality. Suitable tests and service records will be used to determine the acceptability of the stone protection materials. In the event suitable test reports and a service record, that are satisfactory to the Contracting Officer, are not available, as in the case of newly operated sources, the material shall be subjected to such tests as are

* DELETE INAPPLICABLE PROVISIONS.

necessary to determine its acceptability for use in the work. Tests to which the materials may be subjected include petrographic analysis, specific gravity, abrasion, absorption, wetting and drying, freezing and thawing, and such other tests as may be considered necessary to demonstrate to the satisfaction of the Contracting Officer that the materials are acceptable for use in the work. All tests will be made by or under the supervision of the Government and at its expense.

44. Some of the CE Divisions have also developed guide specifications for use by the subordinate Districts. These specifications generally follow CE-1308 but provide additional guidance. Some guide specifications suggest maximum and minimum limits of test values for acceptance or rejection of a stone source.

Quality Tests Used Currently

45. The quality tests included in the guide specification (paragraph 43) are listed below with their designations (U. S. Army Engineer Waterways Experiment Station 1949b):

- a. Petrographic analysis (CRD-C 127).
- b. Specific gravity (CRD-C 107).
- c. Absorption (CRD-C 107).
- d. Freezing and thawing (CRD-C 144).
- e. Wetting and drying (not standardized).
- f. Los Angeles abrasion (CRD-C 145).

The Contracting Officer makes the decision as to which of the above tests and any other tests should be used to evaluate a rock source. In addition, a geological examination of the quarry and a service history of the stone are generally required by the Contracting Officer.

46. Some Districts in the southern United States do not require the freezing-and-thawing test for evaluation of the stone, for reasons of mild temperatures, but usually require the wetting-and-drying test. Most Districts further north require the freezing-and-thawing test but not the wetting-and-drying test. Other tests used on a local basis are

the sulfate soundness test and the ethylene glycol test, described in paragraphs 55 and 56, respectively.

Reliability of the Quality Tests

Sampling

47. The selection of the sample to be submitted to the laboratory for testing can be the most important step in the source evaluation procedure as the test results are only as representative as the sample submitted. Some of the problems existing in the field today can be traced to the sampling. Some guidance is available indirectly in related method CRD-C 100 (U. S. Army Engineer Waterways Experiment Station 1949b) for sampling stone for concrete aggregate. This method prescribes that the samples be taken by the contractor in the presence of a representative of the Contracting Officer. A similar requirement for riprap and other large stone should similarly achieve improvements in representative sampling.

48. It seems possible that the specifications for sampling riprap should be even more detailed, requiring the test samples to be selected by a trained geologist or materials engineer representing the Contracting Officer and conversant with production, construction, and testing. The specifications might also be made more effective with wording to the effect that three or more representative stones of each geological type, each weighing at least 50 lb and generally blocky in shape, should be submitted for testing.

Unit weight, specific gravity, and absorption (CRD-C 107)

49. Tests for unit weight, specific gravity, and absorption are often conducted on that portion of the stone sample remaining after slabs have been cut for the freezing-and-thawing or wetting-and-drying test. The tests are satisfactory as presently conducted.

Petrographic analysis (CRD-C 127)

50. While the petrographic examination in the laboratory is often essential for evaluating the suitability and potential durability of

stone for armor or riprap, it is limited to qualitative rather than quantitative appraisal. Petrographic examination identifies the composition and homogeneity of samples and their general physical condition and should recognize potential parting planes. While the existing method CRD-C 127 (U. S. Army Engineer Waterways Experiment Station 1949b) is directed to petrographic examination of concrete aggregates rather than riprap and armor stone, useful guidance can be found under its ledge rock category. The American Society for Testing and Materials (ASTM) designation is C 295.

51. A new item or a revision of the present one placing more emphasis on features that may be found in large pieces of rock might be helpful. The burden of sampling for the testing of large stones now rests with the geologist doing the quarry evaluation and the sampling. Samples selected should include flaws common to the rock that is or will be produced at the quarry site, and descriptive information should be supplied to aid the petrographer in giving a total evaluation of the rock for its intended use.

Freezing and thawing (CRD-C 144)

52. The freezing-and-thawing test may be the best quantitative test for determining the durability of riprap, provided care is taken in obtaining representative samples and in preparing samples for testing. Special care should be taken to assure that the test slab is sawed perpendicular to the bedding plane. In view of the established usefulness of this test, additional new exploratory work has been undertaken for this study and is included in this report as Appendix A. The appendix examines the effect of the increased size of the test piece and suggests tentatively that more realistic and useful results will come from large test blocks.

Wetting and drying

53. A wetting-and-drying method has never been standardized; therefore, laboratories vary somewhat in the test procedure they follow. Wetting and drying can be a useful test in areas where freezing and thawing is not a problem. A draft standard test method is included in Appendix B.

Los Angeles abrasion (CRD-C 145)

54. The Los Angeles abrasion test is useful in determining the resistance of concrete aggregate materials to abrasion and, accordingly, should have value as an index of durability of riprap stone for certain abrasive environments. Significance of the test in a more general context of large stone suitability is not established. One deficiency of the method is the lack of guidance on preparing samples from large pieces usually received by the laboratory for testing. The usual procedure is to break down enough pieces, each weighing about 100 g, to provide the prescribed total weight, but see the related concern with fragment size in paragraph 55.

Magnesium sulfate
soundness (CRD-C 137)

55. The sulfate soundness test is no longer listed in the guide specifications (see paragraph 43) but is still conducted routinely as a quality test in some laboratories. Some doubt exists that this test reveals any deterioration properties of the stone not revealed by the freezing-and-thawing or wetting-and-drying test. Samples soaked in a sulfate solution will break apart when the solution is absorbed along weak planes or cracks and then crystallizes upon heating and drying. Another shortcoming of this test on large stone is that the test particles are broken from the large stone to a weight of approximately 100 g each, and the breakage in segregation will eliminate weak areas when preparing the sample; test results may thus tend to be too favorable.

Ethylene glycol (CRD-C 148)

56. One test not listed above but required by some Districts is "Method of Testing Stone for Expansive Breakdown on Soaking in Ethylene Glycol," CRD-C 148 (U. S. Army Engineer Waterways Experiment Station 1949b). This test is required when the presence of an expansive clay of the smectite group is suspected.

New Tests

57. Certain other tests are proposed from time to time and some

deserve careful review for applicability. This continuing review process assures that the state of the technology will stay current. One such "new" test that needs to be considered carefully for its potential in distinguishing good stone from marginal or poor stone is the ultrasonic disaggregation test. The application of ultrasonic energy to cause a disaggregation of weak rock has been reexamined recently, and the test has been judged to be promising for testing riprap (Saltzman 1975). Advantages claimed are low cost and short time required to test. Also see DuPuy and Ensign (1965). It remains to evaluate this technique by trial application to actual project testing.

PART IV: DISTRICT AND DIVISION EXPERIENCE

58. Letters were sent in April 1979 to CE Districts in the United States (also the Pacific Ocean and New England Divisions) requesting information for this study on recent field performance and general experience with riprap, armor, and jetty stone. The five specific questions asked in the letter are given in Table 1. Thirty-two of the 38 offices contacted replied by letter, i.e., almost 85 percent. During the study, many telephone calls were made to expand individual case histories or to contact other offices to seek additional information, and ultimately all offices responded with information in one form or another. Many of the responses indicated no problems. Further inquiry revealed that several Districts whose formal reply indicated no problems had experienced some riprap deterioration, but it was considered to be insignificant. The edited responses are presented below.

Lower Mississippi Valley Division

Memphis District

59. The Memphis District responded that they had observed no significant deterioration or cracking of riprap and noted that some of the stone has been in place as long as 50 years. Stone is contracted for on a unit price basis in place. Contractors may provide the stone from any of the 12 approved quarries in Illinois, Kentucky, Missouri, and Arkansas, or from any other source that meets the physical requirements or that has sufficient service record. All stone supplied to this District in recent years has come from commercial quarries.

60. In answer to question 3 in Table 1, the District knew of no case where testing has indicated marginal or poor stone quality but actual performance was satisfactory. Stone from all of the approved sources has had satisfactory physical properties. One quarry, Three Rivers Rock Company, has a layer of shale about 4 ft thick as a seam between ledges of sound stone. The quarrying process involves working down to this layer and then wasting it.

New Orleans District

61. The New Orleans District reports no available information to indicate problems as the result of quarystone deterioration. Foreshore protection failures that have occurred were the result of undermining the blanket layer rather than failure of the stone itself. All stone delivered has been of good quality and has provided excellent protection. The District has no knowledge of stone being delivered that did not meet specifications.

62. Quarrying and handling are the major factors in rock selection. The New Orleans District is restricted by distance and transportation costs as to its sources of stone. Quarry stone is obtained from commercial sources in Gilbertsville and Smithland, Kentucky. Broken concrete has been used on a limited basis and found to provide slightly less than satisfactory protection. The flat, smooth surfaces of the concrete scrap facilitate sliding down the slope.

St. Louis District

63. Deterioration of riprap is not a problem in this District; stone of good quality is readily available at economical distances. The District keeps a list of approved sources, which is constantly updated. The sources of nearly all riprap and armor stone (capstone) in this District are commercial quarries. In two cases, at Carlyle Lake and at Rend Lake, the contractor chose to use large manufactured concrete shapes instead of natural rock capstone.

64. The contractor-selected source for each project is approved in writing by the Engineering Division of this District. This approval process allows control over the production of stone from any individual bad ledges within that source. That is to say, all stone from a source is not necessarily good. Most quarries on the District's approved list have ledges of both quality stone and inferior stone. Poor quality can result from thin bedding, shale seams, mud pockets, soft friable rock, and other characteristics.

65. The type of stone protection or protection system is based on hydraulic design requirements and what sizes and gradations can economically be produced at the quarries in the area. All of the problems

that have been encountered with stone protection in this District have been associated with the very real problem of control of gradation during construction.

Vicksburg District

66. Experience in the Vicksburg District with deterioration of stone protection indicates that the quality of the stone is not a factor. This District has experienced some riprap failures, but they attribute these failures to factors other than stone quality. The severest environment in which stone protection is placed is in the vicinity of hydraulic structures.

67. Quarries that produce the stones for protection are selected by the contractors from a source list provided in the special provisions of the contract specifications. Gradation tests are performed as required during stone production at the quarry. The source list includes only those quarries having suitable rock as indicated by laboratory testing performed by the Lower Mississippi Valley Division Laboratory. All the sources that have been used in recent years are commercial quarries. The majority of the stone comes from limestone or nepheline syenite formations, but there is some production from quartzitic sandstone formations.

68. The closest quarries used by this District are in Arkansas (see paragraph 2, Appendix A), but most stone used to date has been obtained from quarries located near the Mississippi and Ohio rivers because of lower freight charges based on barge transportation. River distances to the more distant quarries often exceed 500 miles. There are other quarries located in Alabama, but they are generally not competitive due to transportation costs. Most of the stone for this District is processed specifically for slope protection; however, quarry-run material is considered acceptable for stone dikes on the Mississippi River.

69. There are no known cases where testing of riprap for projects within this District has indicated that the contractors have utilized stone of marginal or poor quality. The District has no knowledge of stone from a particular quarry having given both good and bad service

since any unacceptable areas are rejected in the initial acceptance of the source. There are a few cases where individual stones have given poor service, but these few individual stones slipped through the inspection processes before or during placement.

Missouri River Division

Kansas City District

70. The Kansas City District cited their experience with graded riprap and bedding material on the upstream faces of dams, on the slopes of outlet channels, and on levee slopes, as well as their experience with less tightly graded revetment stone along the banks of the Missouri River. Most of the riprap is made from limestones ranging from Ordovician to Permian age; there are also two sandstones: one a silica-cemented sandstone of Tertiary age, and the other a calcite-cemented sandstone of Cretaceous age. The sandstones have proven to be durable riprap while the limestones range in durability from fair to excellent. Both commercial quarries and Government quarries have been used as sources of riprap. Along the Missouri River, the rock sources are generally contractor-owned or -leased quarries adjacent to the river, from where the rock is barged directly to the placement area.

71. The major factors involved in rock selection for a project are quality, availability, and cost. If a rock source, even one of marginal quality, can be found near a project, it is used even though a greater thickness of riprap may have to be specified. Rock from required excavation is also utilized for riprap. In rock-fill construction, the larger stones are raked to the upstream face to provide protection. When local rock is not available, high-quality rock from distant sources is used for riprap. The test that the District considers to be most definitive for evaluating rock quality is the freeze-thaw slab test CRD-C 144. Service records of the performance of stone from a given source on past projects are also definitive.

72. The Kansas City District routinely monitors the riprap on all projects. On some projects the riprap is undergoing a slow, continuous

breakdown and occasionally minor repairs are required. This deterioration has occurred more often in Kansas than in Missouri and Iowa. Specific case reviews provided below reveal that the less troublesome Missouri and Iowa rock sources commonly produce from older formations than those in Kansas.

- a. Riprap on the Tuttle Creek Dam, Kansas, is a rather soft, lightweight limestone (Cottonwood Limestone member of Permian age). It was obtained from required excavation for the spillway. The rock was placed in 1959. In 1968 additional rock was required on the upstream face of the dam, and slush grouting was required on the riprap of the outlet channel slopes. On the upstream face of the dam some abrasion loss of the riprap was noted during an inspection in 1975, but the performance of the riprap is considered satisfactory.
- b. At Pomona Dam, Kansas, small cusps were noted in the riprap on the upstream face of the dam in 1965, and repairs were made in 1970 using rock from a stockpile at the project. The original riprap and the stockpile rock were obtained from an onsite Government quarry in the Plattsmouth Limestone member of Pennsylvanian age. It was placed in 1960. The rock is argillaceous with numerous thin shale seams and shaly laminae. On this project the District attempted to combine bedding and riprap together in a single graded material. They have not repeated this design but have since specified a separate bedding layer and an overlying riprap layer.
- c. At Melvern Dam, Kansas, the riprap on the upstream face is also Plattsmouth Limestone. It was obtained from an offsite quarry and was placed in 1972. Placement of the riprap was less than satisfactory, and considerable segregation occurred. During an inspection in 1979, a minor amount of disintegration was noted, and some rock had been dislodged because of "plucking" and ice action. The riprap is considered to be performing satisfactorily. Riprap on the outlet slopes was obtained from two offsite quarries (Burlingame Limestone member and a limestone reef in the Auburn Shale member, both of Pennsylvanian age). No disintegration of this riprap was noted.
- d. Rock groins made of Plattsmouth Limestone were placed along the Kansas River upstream of Lawrence, Kansas, in 1974. During an inspection in 1975, the rock appeared almost completely disintegrated.

- e. Riprap and bedding on Kanopolis Dam, Kansas, was placed in 1946, using a calcareous cemented sandstone, Dakota formation (Cretaceous age) locally known as "Lincoln Quartzite." Some of the rock was obtained from an on-site Government quarry (now under water), but most of the rock came from a commercial quarry located about 17 miles west of Lincoln, Kansas, and about 45 miles from the project. This source was also used for concrete aggregate. Some damage occurred in 1951 at about el 1480* (conservation pool level is at el 1463) and again in 1957 at about el 1487. During an inspection in 1976, it was noted that 2 to 5 percent of the stones had disintegrated and several cusps about 1 ft deep and 20 ft wide were noted at about el 1467. Since 1976, a slight disturbance of the riprap has occurred, but it is not considered significant enough for repair. Heavy discharges in 1948 eroded the bottom and side slopes of the outlet channel downstream of a 90-ft section of grouted riprap. The riprap was replaced. In 1970, the grouted riprap was extended an additional 50 ft downstream on the right side slope.
- f. Wilson Dam, Kansas, was completed in 1964. Calcareous cemented sandstone from a quarry 2 miles south of Lincoln, Kansas, and about 17 miles from the project was used for riprap and bedding on the upstream face of the dam and in the outlet channel slopes, and also for concrete aggregate. The most recent inspection was made in October 1979. The rock was in excellent condition, and very little breakdown or disturbance of the riprap was noted.
- g. Pomme de Terre Dam, Missouri, was completed in 1961. Burlington Limestone formation (Mississippian age) from a Government quarry site was used for riprap, bedding, and concrete aggregate. The most recent inspection was made in October 1976. The riprap was in good condition with very few cracked or dislodged stones. Burlington Limestone is a hard, durable limestone. It makes excellent riprap and concrete aggregate, but the formation does contain bands and nodules of tripolitic chert that must be removed from the final product.
- h. Burlington Limestone was used for riprap and concrete aggregate on Stockton Dam, Missouri. The riprap was placed in 1969. The most recent inspection was made in November 1978. The riprap was in good condition with very few cracked or dislodged stones.
- i. On the Harry S. Truman Dam and Reservoir project,

* All elevations (el) are in feet referred to mean sea level (msl).

Missouri, Burlington Limestone from an onsite Government quarry was used for concrete aggregate and for riprap on the side slopes of the outlet channel. The riprap was placed in 1971 and 1972. The rock was in good condition during an inspection in November 1979. The dam embankment combines an earth core and rock shell. The shell is composed of rather low-quality rock of the Cotter-Jefferson City Dolomite formation (Ordovician age) obtained from the outlet works excavation. The larger pieces (up to 48 in.) were raked to the outer 50 ft of the rock-fill embankment. The major portion of the embankment was placed in 1969 and remained above multipurpose pool level until November 1979. During that 10-year period, considerable disintegration of the rock took place as was expected, but further serious breakdown is not anticipated by the District. The wrap-around sections on the upstream and downstream ends of the concrete bulkhead portion of the dam are protected by Burlington Limestone riprap.

- j. Long Branch Dam, Missouri, was completed in November 1978. Riprap on the upstream face of the dam and on the side slopes of the outlet channel was made from Kimmswick Limestone formation of Ordovician age. The rock was obtained from a commercial quarry about 50 miles distant. The most recent inspection was made in October 1979. The riprap looked good with very few cracked or dislodged stones.
- k. On Smithville Lake, Missouri, the riprap was placed in 1977. The riprap placed below multipurpose pool elevation was produced from the Spring Hill Limestone member of the Lansing Group (Pennsylvanian age) encountered in the spillway excavation. For installation from 10 ft below multipurpose pool elevation to 10 ft above, the riprap was produced from a commercial quarry in the lower 10 ft of the Bethany Falls Limestone member of the Kansas City Group (Pennsylvanian age). Although the riprap was above water level, a minor amount of breakdown occurred within the first year after placement. This deterioration was mostly in rock from the weathered top portion of the quarry ledge. This breakdown is believed to be caused by placement of moisture-saturated rock, (especially the larger, 48-in.-size stone) during the winter of 1976 and 1977. Inspection of the riprap in 1978 indicated the rock breakdown had stabilized. For the remainder of the upstream face of the dam from 10 ft above multipurpose pool, riprap was processed from the Merriam Limestone member of the Lansing Group (Pennsylvanian age) also from the spillway excavation. No serious breakdown of this rock has been noted.

- l. Riprap on Rathbun Dam, Iowa, was produced from a commercial quarry in the Kimmswick Limestone formation located about 140 miles distant. The rock was placed in 1967. The most recent inspection was made in 1974. The rock looked good, and very few pieces were cracked or dislodged. Riprap in the outlet channel was obtained from the same source, and it also looked good.
- m. Revetment stone along the Missouri River from Rulo, Nebraska, to the mouth near St. Louis, Missouri (498 miles), is continuously being eroded, and replacement requires from 200,000 to 300,000 tons of rock per year. Similarly at one lake (Harlan County, Nebraska), the riprap has twice been extensively damaged by severe storms. The rock did not deteriorate but was dislodged by extremely high waves and swells.

73. The District went on to cite two cases with apparent conflict between test results and actual performance of stone.

- a. On one project, Milford Lake, Kansas, a limestone from a Government quarry site was used for riprap. The stratum is zone D of the Fort Riley Limestone (Permian age). The rock has high absorption (6 percent) and low specific gravity (2.20). These test values seem to indicate a low-quality riprap stone, but 16 years of service records show it to be durable. The pores in the limestone are interconnected, and moisture within the rock apparently can escape as freezing begins, and the rock is not ruptured. In 16 years of service a minor amount of abrasion loss has occurred. During an inspection in 1975, ice flow damage was noted. Performance of this stone is considered satisfactory. See paragraph 192 for additional experience with the Fort Riley Limestone in Oklahoma.
- b. Winterset Limestone of Pennsylvanian age was used on the CID levee in Kansas City, Missouri, in 1978. The rock tested good but did not hold up in service, especially the larger (+15-in.) stones, because of incipient fractures.

Omaha District

74. Deterioration of riprap and other slope protection material does present engineering, construction, and maintenance problems in parts of Omaha District. Along that portion of the Missouri River from Yankton, South Dakota, to Rulo, Nebraska, stone deterioration is a major problem. This experience can be generalized to the eastern half of Nebraska since stone used there comes from quarries along the Missouri

River. In the other areas of the District deterioration is not a major problem. The principal factor in the above problems is the fact that the quarries (all limestone) in the area described contain no high-quality rock, and only a few have any ledges of even fair quality rock.

75. There are few, if any, cases where testing has indicated marginal or poor stone, and the rock has performed satisfactorily. However, there have been numerous cases where testing indicated reasonably good rock but it has not performed satisfactorily. In the area described above, there are numerous cases where the rock from one source (quarry and ledge) has given both good and poor service. Apparently, the explanation lies in the variability among ledges.

76. The District answered question 5 in Table 1 by saying that most of the riprap stone used has been furnished from commercial quarries. A relatively small amount has come from required excavation, and in the Dakotas, a considerable amount has been obtained by picking up glacial boulders (field stones) from a wide area.

77. During 1975 and 1976, the District requested from the Missouri River Division Laboratory (MRDL) extensive tests on supposedly good Pennsylvanian limestone from a quarry near Omaha, which has cracked and performed poorly when used as slope protection at two of the Papillion Creek dams. Deficiencies were evident in test methods for this particular case. Results of neither the 12 cycles of freeze-thaw testing on 100-g pieces nor the 20-cycle tests of 2-in. slabs correlated well with the actual service behavior. Only rough judgments of rock quality could be based on the slab tests. The sulfate soundness test indicated acceptable, though perhaps marginal, material. Fifty freeze-thaw cycles of an 8-in. specimen proved to be a more successful test for duplicating service behavior, but the time and expense reduces the value of this procedure as an acceptance test.

78. The MRDL also conducted studies of absorption and adsorption of several quarry rock types available in the District including those used for Papillion Creek dams. Previous work by others (Dunn and Hudec 1965) has suggested that high absorption and, to a lesser extent, high adsorption are characteristics of many nondurable rocks. Other

factors, such as low rock strength and size and distribution of pores, also contribute to the deterioration process. Mr. W. J. Heck of MRDL offered the following conclusions at the 12th CE Division Laboratories Conference in 1977: (a) the degree of saturation, particularly for rocks having more than 75 percent of the total voids filled with water in 24 hr of laboratory immersion, is critical in defining rocks likely to be nondurable under freezing conditions; and (b) critically saturated rocks, having an adsorption/absorption ratio (at 100 percent relative humidity) of 45 percent or greater, are more likely to fail by wetting and drying processes since the adsorbed water will not freeze. Heck recommended that adsorption-absorption test procedures be adopted as a standard method.

New England Division

79. Stone for armor on Division coastal structures is obtained from commercial quarries. Cracking of such stone is potentially a significant problem for approximately 30-50 percent of the source quarries used by the Division's contractors. Any incipient fractures tend to subdivide the stones during the first years of freeze-thaw cycles. Incipient fractures are normally caused by operational procedures in the particular quarry. An example would be a quarry normally producing aggregate for concrete (with high powder factor and heavy fracturing) but incidentally stockpiling and selling occasional oversize pieces for armor stone. The presence of this condition is identified in the approval process during the quarry inspection, and the construction inspection forces exclude this material from use in the structures.

80. The major factors involved in selection of rock for riprap are largely dependent on the type of structure involved. Rock of lower quality from required excavation may be used in a structure if it is cost-effective. As an average, about 80 percent of riprap requirements for dams in the Division have been obtained from structural excavations at the project site, and riprap design is based on the available rock.

81. Three factors were identified and discussed as being generally

relevant to the New England states. The severe environment was ranked most important since both coastal and inland structures suffer a severe freeze-thaw climate. The second factor, in this case a positive one, was plentiful sources. Igneous rocks for armor and jetty stone are available along the entire coast. Stone availability, however, is becoming increasingly affected by local zoning regulations. The maximum size of stone from any single quarry (a major concern) is usually controlled by the rock type and geologic structure. Finally, the Division cited quarrying, handling, and contract procedures as of importance. The contracting firms and quarry operators dealing in armor and jetty stone generally have had considerable experience in construction of shore protection structures, and very little difficulty occurs as a result of contractor procedures.

82. Testing for the Division has been generally indicative of the quality of stone and predictive of its service as armor stone. The decision as to which test is conducted is made after a geologist makes a megascopic examination of samples submitted for testing. No stone is accepted that has a saturated surface-dry density of less than 162 lb/cu ft. This criterion normally eliminates rock with high feldspar content, thus assuring soundness and good weathering characteristics of the stone. The Division has found that stone from a single source will give similar service at different projects. The single source may vary in regard to size of the stones available, but mineralogy, geological structure, and quality are typical and more or less constant.

North Atlantic Division

Baltimore District

83. Generally, deterioration or cracking of riprap, armor stone, and jetty stone does not constitute an engineering, construction, or maintenance problem in this District, as only material that has passed all the required tests is approved for use on the project. The major factor involved in selection of rock sources is the severity of the weather that can be expected. Source distance and cost are also

factors to be considered; however, because the material must be relied on to function as designed, the quality requirements are not reduced for any reason.

84. Many of the District's projects are located in or near sedimentary rock areas, in which the materials range from poor to fair in quality. Consequently, stone of high quality may have to be hauled from distances up to 100 miles. Some contractors try to obtain large stone from their excavations, but the difficulty they have in meeting the required quality for the stone usually prevents its use; in a few cases, some sandstone and limestone have been usable. When the project is far from a source of quality rock and for parts of the project where quality reduction will not affect safety, this District may use material called "dumped rock" instead of riprap. The limitations on this material are a maximum and minimum size along with an average size. Dumped rock is placed in a thicker zone than riprap.

85. The District reported that material that shows poor or marginal quality in testing has not been placed. In one isolated case, stone that appeared to test good to excellent in quality failed to perform well after placement. This problem occurred because of improper sampling techniques in which a small hand-size sample was taken. The stones broke in service along partings, beddings, and joints, which were not present in the small sample.

86. If two or more horizons or zones of rock are present, samples from each horizon are tested. Stone may be produced only from zones or horizons that have passed the tests. Nearly all riprap and all of the armor stone and jetty stone come from commercial quarries since they have a high degree of quality control

New York District

87. The New York District has had some experience where riprap, armor stone, or jetty stone has been subject to deterioration. Two projects where deterioration occurred were Manatuck and Patchogue River jetties. Both structures required rehabilitation in the late 1960's. The basic cause of the deterioration was attributed to the poor quality of stone originally placed in the jetty and what was probably an undersized gradation for the stone.

88. The need for hard, durable stone to withstand the severe environment is usually foremost in rock selection by this District. Rock sources are plentiful in the region, and costs of transportation and acquisition do not generally cause major problems. Testing and performance data have consistently been in agreement. All riprap, armor stone, and jetty stone used by the New York District come from commercial quarries.

Norfolk District

89. There have been two major uses of quarried stone in the Norfolk District: in the rock shell for Gathright Dam and in protection for various shoreline structures. The shell of Gathright Dam is composed of hard limestone quarried within the reservoir area. The limestone shell was placed trouble free, and since completion in 1978, there has been little deterioration.

90. In the past 25 years, there have been 14 shoreline structures, including revetments and jetties, designed and constructed by the District. The riprap, armor stone, and jetty stone used for the construction of these structures have all come from the Piedmont of Virginia along the so-called Fall Line. Most of the quarried stone is a coarse-grained, hard granite with the remainder being an equally hard gneiss. There were no design or construction problems with either rock type, and deterioration and cracking have been nonexistent even on the older structures. Igneous rocks from the central Piedmont of Virginia have been used extensively in the region for all types of construction.

91. The major factors involved in the selection and performance of quarried rock used by the District is source plentifulness, source distance, and high quality. The rock shell for Gathright Dam was quarried less than 1 mile from the damsite and was of good quality for shell material. The granite and the gneiss quarried in the Piedmont region are very high quality due to their weather-resistant characteristics. Many quarries are located on major rail lines or near navigable rivers along the Fall Line area of the Piedmont, which is less than 100 miles from the entire coastal area of Virginia. Transporting the stone is, therefore, relatively economical.

92. There have been no cases where testing has indicated marginal or poor stone quality but service after placement has been satisfactory or vice versa. Also, the District has had no projects where stone from one source has given both good and bad service.

Philadelphia District

93. The only problem experienced in the Philadelphia District is the deterioration of riprap at Prompton Dam. Since completion of the dam in 1960, some of the riprap placed on the upstream slope has deteriorated. The source of the riprap was required excavation in the spillway. It appears that the selective method of excavation, which was required by specifications, was not carried out satisfactorily in the spillway excavation. The rock placed as riprap included material susceptible to weathering and breakdown as is now occurring. Except for this one case, there has been no problem with deterioration or cracking of stone.

94. The major factors involved in rock selection are size, gradation, and source distance. Of considerable importance in the generally satisfactory experience of the District has been the plentiful supply (sources) of stone ranging from good to high in quality. District sources have included commercial quarries, onsite quarries, and required excavation such as indicated above.

North Central Division

Buffalo District

95. Some of Buffalo District's disposal area dikes, armored with large-size stone (+10 ton), have experienced some degree of breakdown in the form of stone cracking. Postplacement cracking causes a reduction of stone sizes, which could eventually lead to premature maintenance costs or in some cases failure of the structure.

96. The major sources of stone are commercial quarries in Silurian to Devonian limestone/dolomite and in Silurian sandstone, with the former being predominant. A number of factors are involved in the selection of stone sources for District projects. These factors

include: (a) producer's capability to quarry required stone sizes (controlled by strata thicknesses), (b) stone specific gravity, (c) distance from quarry to project site, (d) availability of water haul, (e) quarry operator's interest in producing required materials, (f) available laboratory test records, (g) geologist's quarry reports, (h) available service records, and (i) cost.

97. Available service records are equally as important as laboratory testing results in the determination of the suitability of a given stone source. For instance, the Berea sandstone from Cleveland quarries at Amherst, Ohio, will fail most laboratory durability tests (specifically, the freeze-thaw test), yet the stone has been used in breakwater construction along the Lake Erie shoreline for the past 100 years and has demonstrated excellent durability. The durability is attributed to case hardening of the sandstone.

98. Stone from any one source is rarely homogeneous. Quality can vary as quarry operations proceed both vertically and laterally. Usually, as a job progresses, changes in stone character or quality are detected by quality control-quality assurance. Other factors, such as stress relief, inappropriate blasting and handling techniques, and winter quarrying as related to freeze-thaw susceptibility, probably have all played a part in those cases where the service record of a given stone source has not been consistent.

Chicago District*

99. The District has had problems with cracking of stone used to armor rubble mound dikes. Stone on the dredge spoil disposal area at Milwaukee deteriorated appreciably during the first 2 years of construction (1973-1974) before a change was made to a source of better stone at a greater distance. Dolomitic limestone from the original quarry was found to be of marginal quality by freeze-thaw testing in comparison with the dolomite that was used subsequently. This case illustrates the common preference of the contractor for a local quarry

* Information was obtained from District personnel during visits to projects, rather than by letter response to the questionnaire. This District is identified with others by a footnote in Table 2.

in order to minimize transportation costs, but often at the expense of some stone quality (see paragraphs 17-20).

Detroit District

100. Depending on structure location and type, deterioration or cracking of stone has resulted in problems varying from minor to significant. In the majority of problem cases, most maintenance is required at the lakeward end and lakeside reaches of dikes and similar structures. The primary cause of the deterioration is believed to have been that during construction, the contractor quality control personnel often overlooked hairline cracks in the stone. These cracks are believed to be the result of excessive blasting forces. After placement, the undetected cracks in the stone opened up from freezing-and-thawing and wetting-and-drying forces.

101. The specifications provide listed stone sources that have a good service record and that have been tested, particularly those determined to have stone meeting quality and size requirements. Even though a stone quarry is on the list of sources, a quarry inspection is performed jointly by Foundations and Materials personnel, construction personnel, and contractor quality control personnel prior to the start of production of the stone for the job. During the inspection, samples of the stone representing the sizes and the quality required are marked and placed in a prominent part of the quarry for reference. If there is any doubt that the stone quality is not as good as previously found, new tests are run. If the stone is found after the testing to be not of the quality required, then a new quarry is selected.

102. The contractor may choose to obtain the stone for his job from the list of sources, or he may designate a quarry not on the list. If he does the latter, the stone must be tested for quality and meet the same requirements as for the stone from the listed sources and as specified in the contract. The CE will test one quarry at no cost to the contractor; additional testing is at the expense of the contractor. Quarries are retested periodically where a significant change in the product is suspected.

103. Quarries are only listed for the maximum sizes the stratification could produce. If seam spacings are less than the stone sizes required, stone samples with seams included are tested at the Ohio River Division Laboratory. The tests are performed to determine if the seams open during freezing and thawing or wetting and drying. As a result of recent problems, contracts now specify that no stone be accepted that has been blasted during winter months.

Rock Island District*

104. The Rock Island District reported one incident of riprap deterioration where the stone had been obtained from an unsuitable part of a quarry. The problem has been rectified subsequently. Elsewhere, some of the 4-ft derrick stones at the ends of stilling basins at Red Rock and Saylorville Dams have sustained cracking over a period of 6 to 10 years, but no compromise of the design function is anticipated.

105. This District indicated that they rely more on previous experience with stone types and sources of the region than on laboratory testing. However, tests for riprap and aggregate by the state Departments of Transportation are taken into consideration. Two methods of evaluating stone semiquantitatively have proven useful. First, representative chunk samples are subjected in the office to as many as 100 freeze-thaw cycles and examined for indications of deterioration. Another group of large samples is set aside in the quarry, examined, and photographed before and after a 1-year exposure. Rock that endures with insignificant signs of progressive deterioration is judged acceptable.

106. Limestone from one large quarry in Iowa has proven to deteriorate by cracking when quarried after mid-September and placed immediately on a project. The cracking is well advanced by the following spring. Therefore, contract provisions either require quarrying before the fall or specify a 1-year stockpiling period. Results of these

* Information was obtained from District personnel by telephone, rather than by letter responses to the questionnaire. This District is identified with others by a footnote in Table 2.

practices are satisfactory. The District notes that causes that have been suggested are the freezing of in situ water and release of residual rock stress.

St. Paul District

107. The District seldom has a problem with deterioration of riprap or armor stone. Problems usually occur only when a geologist or materials engineer is not involved in the selection or approval of the source.

108. Very cold winters with attendant freeze actions necessitate the use of a high-quality stone. The St. Paul District is fortunate to have sources that can produce stone of high quality, either quarry material or glacial field stones. Therefore, although many quarries exist that produce marginal to worthless material for riprap, the District can specify and use only the better materials at little or no increase in cost. In the Red River area, only field stone is available locally. If quarry stone is required, it is shipped from a distance. Except for this field stone, almost all rock comes from commercial quarries or mine waste areas. On one dam the rock came from required excavation, but selective processing was necessary.

109. Much of material rejection is based on the geologist's observations. Much rock could pass the laboratory tests but is not judged to be satisfactory because of seams or joints. This deficiency is generally quickly recognized, and further testing is unnecessary. A single quarry may contain both good and bad material, but the experienced geologist delineates the bad layers or zones from otherwise suitable rock.

110. The keys to obtaining satisfactory stone in this District seem to have been: (a) ample supply of good sources; (b) well-trained geologists; (c) good working relations among geologists, construction representatives, and engineers responsible for rock design; and (d) the interest that the geologist and design engineer maintain in the rock before, during, and after construction.

North Pacific Division

Alaska District

111. In the recent past, the Alaska District has had little difficulty with rock quality; however, a significant percentage of completed projects are post-1964. While 15 years may not represent long service experience, the rock has been subjected to the severe environmental conditions of the arctic and subarctic. Quality does not appear to be a problem.

112. Armor rock problems usually are centered around size, accessibility, and production restrictions. Finding adequate size rock has been a problem. Even when accessible, environmental regulations often prevent economic development of public sources. Consequently, the District has relied heavily on private quarries. Hopefully, with settlements of Native Land Claims, more sites will be available. It is anticipated that most of these additional sources will be privately owned also.

113. In the past 5 years, the District has had rock that failed the ethylene glycol test for expansive minerals while service history from the same source was quite good. While using this test for their own information, the District does not use it as a contract requirement. The District noted, finally, that significant quality variation within the same source has not been a problem.

Portland District

114. Deterioration or cracking of large jetty stone has been a significant problem in the use of certain rock types for many years. Some problem types, such as poorly cemented sandstones, have been eliminated in recent years by more stringent test requirements, but other problem types are still used occasionally. Marine basalts, volcanic breccias, and basalt flow breccias with their heterogeneous compositions and diverse physical properties now constitute the primary problem rocks. This condition is most significant along the Oregon Coast where marine basalts are the principal local rock type that occurs in jetty stone sizes.

115. The major factors involved in rock selection and performance include: (a) project design considerations, (b) stone quality, (c) stone size, (d) availability, (e) haul method and distance, (f) quarrying operations, and (g) environmental regulations. Design considerations, such as structure size, wave and current action, construction methods, and required longevity, are basic for determining rock selection and performance. Riprap and jetty stones utilized for structures with normal life expectancies must meet stringent District stone quality requirements. Large stone sizes required to meet design substantially reduce the number of available rock sources. Where suitable stones are not available from local sources, long hauls by barge or truck are necessary. Quarrying operations, including blasting methods and handling restraints, can further limit production of acceptable stones. Environmental regulatory restrictions can delay or prohibit stone production from otherwise suitable rock quarries.

116. Marginal or poor stone quality has been indicated by laboratory tests for some quarries that have had satisfactory service records. This conflict has arisen mostly since accelerated expansion (ethylene glycol) testing has been required, a relatively recent addition. The accelerated expansion test has helped eliminate some rock sources that contained unsuspected montmorillonite or other expansive minerals, but as the foregoing conflict indicates, the test may be somewhat more severe than is absolutely necessary under operating conditions.

117. Several rock sources have produced stone that gave both good and bad service. Most frequently, these sources include nonhomogeneous rock types or a different rock type that was exposed as quarrying advanced. Marine basalts and volcanic breccias commonly include both good quality rock and unacceptable rock distributed irregularly. Good quality basalt has often been observed to pinch out or grade into unacceptable flow breccia.

118. Rock sources in the Portland District are almost all commercial quarries. Except for those on Government property at dam construction sites, the District does not explore or take responsibility for providing rock sources. The District does determine probable rock

sources for feasibility studies and also prepares cost estimates for production of required stone quantities. Because of the high-risk factors involved in opening new quarries (see paragraph 119), most contractors prefer to bid based on the use of rock from existing commercial quarries with known service records.

119. The greatest difficulties in the past have been associated with the use of new rock sources, from which the contractor has obtained unacceptable and marginal stone for delivery to the construction site. Such jobs appear to have been bid with little or no subsurface exploration and only minimal visual observations at the proposed rock sources. Yields of good quality, large stones from new rock sources frequently are much lower than anticipated because of inaccurate initial estimates and poor quarrying methods. Delivery of marginal stones results in considerable inspection difficulties. Visual inspections are often arbitrary and may not be acceptable, and laboratory testing of numerous marginal stones necessitates very high costs and long delays.

120. The District summarized by saying the primary economic factor in many riprap and most jetty stone projects is obtaining good quality stones in sufficiently large sizes. The District has insisted upon high stone quality to maintain revetment and jetty life as long as possible in the belief that this is less expensive than more frequent repairs with poorer quality stones. The few recent stone failures were mostly not due to poor stone quality but rather to design or foundation problems. Suitable quarries containing good quality, larger stone sizes are, however, very limited and localized only in specific geographic areas. Most of the stones currently used for coastal jetty construction projects in southern Washington and much of Oregon are barged considerable distances from a single commercial basalt quarry on the Columbia River east of Portland (Fisher quarry).

Seattle District

121. The Seattle District employs various types and sizes of rock: (a) for armor and jetty stone in a variety of coastal and inland water environments, (b) for riprap on riverbank protection projects, and (c) for related uses on major civil works projects. Deterioration

of stone is rarely a problem except on some emergency work where less attention has been given to the quality of stone used. In some cases, the District has upgraded or repaired rock work done by others. Occasionally, portions of the rock used by others have been of inferior quality and were removed and wasted. Production of the required size in stone from a quarry is occasionally a problem due to natural jointing in the rock.

122. The major factors involved in rock selection are project purpose and longevity, availability and quality of material, and cost. Usually the District does not designate a rock source for jetty or levee work, but for the Government estimate they use the closest material available that will meet specifications, in terms of size, quality, and quantity. Through many years of experience, basic rock quality test criteria have been developed that can be related to rock performance. Some deviation from the criteria may be allowed considering the type of project and cost of locally available materials. Specifications for jetties and breakwaters are very tight in terms of rock quality, but specifications are relaxed somewhat for riverbank protection work. The rigors of the environment are therefore taken into consideration. For rock work (new construction) at major civil works projects, except for breakwaters, jetties, and bank protection, rock generally comes from required excavation or excavation modified to produce the quantity needed. For breakwaters, jetties, or bank protection, prospective quarry sites are investigated and the material is tested to determine longevity characteristics prior to final selection. Except at major civil works projects involving rock excavation, all rock comes from commercial quarries.

123. Regarding marginal quality rock that has provided satisfactory service, the District cites an excellent example from an older jetty project. The breakwater at Neah Bay, Washington, was originally constructed of welded agglomerate that fails both the freeze-thaw and sulfate soundness tests. In the low freeze-thaw cycle marine environment of Neah Bay, the rock has generally performed well.

124. Variability of rock quality within one quarry is more the

rule than the exception because many of the sources contain volcanic rocks or metasediments. However, the specifications are written so that only the better quality rock can be used, i.e., the District does not approve sources of rock per se. Sometimes the quarry operators will furnish the remaining rock to non-CE projects with less stringent specifications.

Walla Walla District

125. There have been no cases within this District where the deterioration of the riprap cover on levees or embankments has caused the failure of those structures. Major repairs to the levee slope protection fronting the cities of Pasco and Kennewick, Washington, and the railroad fills within McNary Reservoir, Columbia River, were required because of the inadequacies of the riprap, which were not attributed to rock quality.

126. Deterioration of riprap stone occurred on a short reach of the SP&S Railroad along the Crow Butte portion of the relocation for the John Day Lock and Dam project, Columbia River. The basic stone type was basalt, but the contractor obtained material of poor quality, including flow breccia, talus, and excavated stone, from an unapproved source. Deterioration proceeded rapidly because of the presence of clay minerals in the rock. Structural failure has not resulted from the poor quality rock because the reach of slope protection has only limited exposure to pool action. Corrective measures to date have consisted of stockpiling a supply of suitable stone nearby in anticipation of repair requirements.

127. Some deterioration of riprap has also been experienced at the Jackson, Wyoming, local flood protection project where a zone of weathered rock in the quarry was incorporated. The rock was tentatively classified as andesite with a unit weight of 170 lb/cu ft. The poor quality material was estimated to be less than 2 percent of the material placed, and it was widely disseminated over several miles of the slope protection. The low-quality zone had been designated by specifications to be avoided by selective quarrying, but some rock from the zone was used nevertheless. Closer construction control could have

reduced the amount. Local failures of the riprap protection have occurred at this project, but stone deterioration has been confined to isolated pieces and has not been definitely established as a direct cause of the failures.

128. Unapproved rock was also used during placement of riprap on the upstream face of the south abutment of Lower Monumental Dam on the Snake River. A zone of weathered, poor quality basalt overlying the approved quarry source material was not entirely stripped and wasted. The poor quality material was incorporated throughout the riprap, and individual pieces have exhibited considerable disintegration. Detailed studies of the material have not been made, but deterioration appears to be due to weathering of constituent clay. The deterioration of scattered pieces within the slope protection has not caused any failures to date, but the problem area is under continued observation as part of the normal maintenance and operations for the dam as well as the periodic inspections for the dam safety program.

129. Experience gained from the projects mentioned has led to the careful scrutiny of all future riprap quarries for the presence of the deleterious clay materials, and the District now tests all potential sources using CRD-C 148 (see paragraph 56). Since then, minor occurrences of breakdown due to clay content have been experienced, but repairs have not been necessary. The other tests the District may use alone or in combination are CRD-C 107, 127, 137, 144, and 145 (see paragraphs 49-55), with the choice depending upon intended use and knowledge from previous testing or experience of that particular rock type.

130. The District also recommends that field observations be made on new sources. At surface exposures, fracture pattern and spacing, size of detached fragments, weathering characteristics, fabric, hardness, and brittleness can be observed. Subsurface investigations and test quarries can be directly useful under certain circumstances. Also recommended is the review of the service record of the particular stone or similar types of stone on existing projects.

Ohio River Division

Huntington District*

131. Huntington District reported that they have never had problems with stone deterioration in the sense that repairs have been necessary. Stone has deteriorated on some older slope protection projects, but the low-energy nature of the particular hydraulic environments has made repairs unnecessary.

132. Riprap for use in the District comes mostly from commercial sources and from required excavation. Most commercial stone is produced from limestone horizons of appreciable thickness, but such thick strata are uncommon in the District. Though limestone is the preferred material, most of the sources are located in Indiana, central Kentucky and Ohio, and eastern West Virginia at considerable distance from many projects. Therefore, the distance to the source and, in turn, the cost are major factors for consideration in riprap projects and other work requiring large stone.

133. Sandstone of suitable quality occurs in the District and, where encountered in required excavation, has been used for protection. The required excavation usually produces a quarry-run gradation directly, and this gradation may not be compatible with design requirements (graded stone on bedding or filter cloth). Processing of required excavation rock to meet graded riprap specifications has not been regularly practiced in this District, but some relatively high-quality sandstone from required excavation was processed at the R. D. Bailey project. Elsewhere, the District's experience indicates that processing degrades the material and produces more fines. Some designs call for quarry-run rock with no processing except for removal of oversize blocks; also some beneficial removal of fines can be accomplished routinely by shaking the rock bucket while loading out the shot rock.

134. Local rock is usually chosen on the basis of service records

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or other familiarity with particular rock types rather than on the basis of laboratory testing. It has been through such experience that the District recognizes the acceptability of some sandstones (once they have been placed) that are marginal at first appearance. The durability of such sandstone seems to improve with time and is ascribed by the District to a case-hardening phenomenon.

Louisville District

135. The District has experienced no problems with graded riprap. However, three of their dams have experienced deterioration of embankment protection where quarry-run stone was utilized. The problem was aggravated in that the specifications did not restrict tracked equipment from the material during placement. This traffic tended to break up the larger stone. Two of the projects have since been overlaid with graded stone within the zone of normal pool fluctuations.

136. Stone is readily and economically available within the District. The high cost of other methods of protection therefore favors the use of stone. Quality stone from required excavation is used as riprap as far as practical, but the bulk of stone comes from commercial quarries.

137. Marginal quality stone has been used for protection on small projects where quality stone was not readily available. As far as is known, this material is performing satisfactorily. There are no known cases where stone from one source has given both good and bad service.

Nashville District

138. Deterioration or cracking of riprap has not constituted engineering, construction, or maintenance problems in this District. Riprap at one project deteriorated, but only because material from an unapproved zone in the source quarry was used. The District has had no cases where the stone from an approved source has given both good and bad service.

139. The major aspects of rock selection and performance have not really included factors such as severe environment, contractor procedures, high cost, and quarrying and handling. Selection has been based on the suitability or quality of the stone, the quantity

available from the source, and the distance of the source from the project. Riprap in this District is usually procured from commercial quarries.

Pittsburgh District

140. This District responded that they have had no deterioration problems when stone is selected specifically for riprap. Some early earth dams have used as their upstream and downstream riprap zoned areas of random sandstone fill that did contain rock with shaly bedding. These zones of rock fill were 10 to 50 ft thick, and the inferior material has constituted no problem.

141. Riprap is always selected on its availability and performance-tested durability. Generally, if the option of source is left to the contractor, he selects the most cost-effective and available source within the limits of the specifications and requirements. All sources and rock types are subject to approval by the Geotechnical Branch. Most sources are commercial quarries. Quarry areas have occasionally been designated at the project, and on other projects rock from required excavation has been specified. These noncommercial materials have performed satisfactorily.

142. The rock types used in the Pittsburgh District are limestone and sandstone. Limestone used for riprap passes the qualifying tests for aggregate for concrete. No durability problem has ever been experienced with this rock. Limestones not of aggregate quality contain such a large amount of argillaceous material that they are completely unsatisfactory for any kind of exposed protection. Sandstone in the Pittsburgh District has always been satisfactory as a riprap when it is relatively unweathered. Sandstone usually resists tests such as wetting and drying and freezing and thawing. Other tests, such as the destructive tests to which concrete aggregate rock is subject, will fail the sandstones completely. Experience has shown the District that sandstone, once it is in place as riprap, maintains its particle size and shape and performs entirely satisfactorily. Testing is thus usually not required.

Pacific Ocean Division

143. Only two kinds of rock are available for slope protection in this Division, coral reef limestone and basalt. Both rocks are fragile and require controlled quarrying and handling. Despite the softness of coral limestone (3 on Moh's hardness scale), the rock has proven extremely serviceable when used as dimension stone, considering exposure to wave and other forces of nature. Most coral limestone dimension stone and riprap comes from quarries located on the ocean side of atoll islands.

144. Basalt is not generally considered a potential source for dimension (quarried) stone because of its fragile, glass-like nature and critical response to blasting. There are no quarries producing basalt dimension stone on a primary basis in the Division, and only one quarry recovers large pieces as a by-product from quarrying for aggregate. Basalt field stones (boulders) are more frequently used but have the drawback of having a much wider range of specific gravity because of the variety of parent lava flows.

145. In Hawaii, the basalt field stones are collected by contractors from private landowners, generally from the sugar cane fields from which they have been removed. Huge stone piles have accumulated around the margins of the fields. Despite the costs of sorting and handling, these refuse stones are competitive with reinforced, shaped concrete units, especially in sizes below 8 tons. Occasionally, riprap size stone is available from commercial quarry operations.

146. The rounded shape of field stones makes them difficult to place on a revetment as well as susceptible to dislodgement by wave action. The delicate, fragile nature of coral limestone results in loss of a few pieces by breaking during quarrying, sorting, or placing. Once in place, however, both limestone and basalt stones resist deterioration and have been quite satisfactory.

147. Basalt and reef limestone in practically all cases meet the standard, basic, laboratory testing. However, the present testing methods are not always satisfactory in quantifying the suitability and

quality of these two rocks. Exposure after quarrying causes beneficial calcification and case hardening in coral reef limestone while, on the other extreme, the release of stress locked into basalt during cooling from original lava flows may facilitate deterioration. In the absence of better testing procedures, a simple field test is used whereby selected pieces are dropped 5 to 10 ft on other stones to confirm durability.

South Atlantic Division

Charleston District

148. Charleston District reports that deterioration and cracking of stone (riprap and jetty) does not constitute a maintenance problem. However, the District normally uses very durable granite for this purpose. All stone has come from commercial quarries. The major factors involved in selection of stone are durability of the stone, haul distance, availability, and purpose for which the stone will be used (i.e., slope protection, rockfill, etc.).

149. The District cited one project of special interest to the present study, a jetty project that was designed to use a low specific gravity (2.30) limestone as foundation material. As construction progressed, it was observed that the contractor's "method of operation" required the rehandling of the foundation blanket stone several times. This process readily broke down and crumbled the limestone resulting in production of an excessive amount of fines. These fines washed out during placement with the loss due primarily to the turbulent action of breaking waves (as in a surf zone). Test results indicated that the material was satisfactory. However, the District's quality assurance team felt that the stone was of marginal quality and proposed a change order to require the contractor to use a granite-grade stone for the foundation blanket. The proposal was accepted and to date the new foundation blanket has performed successfully.

Jacksonville District

150. Deterioration or cracking of riprap or jetty stone has

never been a construction or maintenance occurrence in this District. The major factors involved in rock selection for a structure are source distance and unit weight required by design.

151. Native Florida limestone is generally not satisfactory for jetty armor stone but performs adequately for bedding stone and slope protection in nonsevere environments. Virtually all material used is either granite or dense, massive limestone from a neighboring state. In Puerto Rico, an abundance of suitable stone is available, but problems exist in obtaining continuity of production and consistent compliance with gradation requirements.

152. Almost all the stone is obtained from commercial quarries. A very small amount of rock for riprap is obtained from required excavation when suitable.

Mobile District

153. The Mobile District has experienced problems with riprap at Jones Bluff Lock and Dam, Okatibbee Dam, and Miller's Ferry Lock and Dam. The source for all three projects was a quarry producing from Mississippian dolomitic limestone strata. The quarry had previously supplied acceptable stone, but problems developed when cherty stone was obtained outside the area previously designated as acceptable for riprap. This quarry is no longer used for riprap by the District. Among massive and thin-bedded varieties, the thin-bedded chert seems to have been most troublesome.

154. Seemingly weaker sedimentary formations, as young as Cretaceous in age, have been used with satisfactory results on projects distant from the preferred sources near Bessemer. The District finds that massive ledges of graywacke sandstone and sandy limestone produce stone that may undergo some surficial weathering but otherwise endure with no serious progressive disintegration. The durability is apparently not attributable to a case-hardening phenomenon.

155. The major considerations for rock procurement are rock quality, source distance, available supply, and quarrying and handling. The District has generally used commercial quarries. Most projects have been in areas that have not had good rock sources onsite. All

quarries situated within a reasonable distance of a job site and capable of producing riprap in the quantities required are tested. If a contractor finds a new source or establishes his own source, the District will test the rock prior to allowing the rock to be used on the project.

156. Stone for coastal projects is barged from as far as Kentucky (via the Mississippi River and coastal waterways) or comes from granite quarries in Georgia or Alabama. The District has noted occasional scheduling and delivery problems with rail haulage. Truck haulage as far as 120 miles is commonly feasible, particularly where an extra unloading-loading increment can be avoided.

Savannah District

157. Problems with stone have generally been related to production of materials that meet criteria for shape and weight rather than with rock quality. The District finds that when the weight criterion is applied, the stone dimensions frequently do not meet the criterion for layer thickness. The District has also experienced difficulty with particle elongation standards, which has contributed to the size-weight problem.

158. Rock is selected by the contractor either from sources previously tested and listed or from new sources. The sources listed are usually those near the project that can produce satisfactory rock. Contractors occasionally propose other sources, either of lower overall quality but closer to the project or beyond the normal economical haul distances (special factors may make the long haul feasible for a particular contractor). Most stone used in the District is gneiss or granite, but infrequently limestones are proposed by contractors and occasionally are approved for use. Some quarries have indicated that they cannot physically or economically produce the stone in accordance with the guide specifications. Some limestone quarries are capable of producing both acceptable and unacceptable materials. Sources with such variability are usually not approved.

159. Commercial quarries have been used as sources for beach and harbor protection. Required excavation is often used for dam and cofferdam protection material. Bridge abutment protection has generally been

from commercial sources with local sites being used occasionally.

Wilmington District

160. The District responded to questions 1, 2, 3, and 5 (Table 1) as follows. Armor stone and jetty stone deterioration or cracking is not a problem. Riprap deterioration on one flood control dam has become a maintenance problem since construction completion in 1974. Severe environment is the primary factor involved in selection of rock for coastal structures. Severe environment, plentiful sources, and source distance are equal factors in the selection of rock for inland structures. Good quality rock is available locally in the Piedmont and the mountain regions of the District and is within economic haul distance from the coast.

161. All stones placed in recent years for coastal structures (armor stone, jetty stone, etc.) have been obtained from commercial quarries. Most riprap for inland structures was obtained from commercial quarries also. There are no documented cases of testing and service records being in conflict.

South Pacific Division

Los Angeles District

162. The Los Angeles District reported that, in general, there have been no problems of cracking or deterioration of stone used on projects. There were serious problems on the Santa Clara River and Santa Maria River levee projects in 1960 where the original stone for slope protection deteriorated very rapidly. The stone passed extensive testing (specific gravity, abrasion, wetting and drying, etc.), which was required at the start of both projects since the quarries were new. In both cases, changes in the rock developed that were not visually detectable as excavation into the quarries progressed. The rock for both projects is volcanic--a diabase at the Santa Clara project and basalt at the Santa Maria project. The deteriorated sections of both projects were overlaid with material from new sources that again passed all tests. Several sources were used at Santa Maria, and the materials

were mixed sandstones and dolomites. Recent levee inspections have found that since 1964 when the overlays were placed, deterioration of the overlay stone has occurred to as much as 50 percent. This deterioration, however, has progressed at a slower rate than deterioration of the original facing stone.

163. The Los Angeles District experience indicates a conflict can exist between laboratory test results and service records as in the examples described above. The District has also had the opposite experience. Stone from Connally-Pacific quarry on Catalina Island has been extensively used in ocean projects in southern California since at least 1936. No visible deterioration has occurred on stone in place, yet wetting-and-drying tests on some samples have indicated distress and occasionally failure. In the final determination, service records take precedence over the testing unless petrographic analysis indicates a significant change in the type of stone from that previously used. If a new source is used, the District performs the routine testing. The stone is then evaluated during periodic inspection to determine its serviceability.

164. Rock is extremely variable in southern California; sources with good material frequently have areas of unsuitable material. A few quarries furnish sandstone or dolomite that frequently contains pockets of shale, soft sandstone, etc. Most quarries in the District contain crystalline rocks of either granite or volcanics. These quarries tend to be more uniform; however, structural conditions, such as faulting and fracture zones, are paths for weathering, which render the stone unsuitable in those zones. For each project, a District geologist inspects the proposed source to determine its potential to furnish suitable material. Project and quarry personnel then must monitor the rock selection at the quarry to ensure that unsuitable material is not placed at the project.

165. The greatest single factor in the selection of stone used on a project normally is the availability of a commercial quarry. In southern California and Arizona, the availability of commercial sources is very erratic. The San Diego area has several good quarries; in

Santa Barbara, the nearest source is 30 miles; and in Phoenix, no known sources exist for possibly 100 miles. Most restrictions are due to environmental and cultural constraints. Housing developments encroaching on established quarries have gradually caused many of them to close.

Sacramento District

166. The Sacramento District has no recent experience with armor stone and jetty stone. Experience with riprap slope protection for dams and levees has been extensive. The following projects summarize experience with slope protection for dams.

- a. At Terminus Dam, the slope protection rock came from the spillway excavation. Removal of confining pressures, wetting and drying, and freezing and thawing have resulted in cracking and breakdown of the rock into small pieces. About 5 percent of the rock has experienced this deterioration. The riprap zones on the face of the dam were made a minimum of 3 ft thick with a maximum of 12 ft on the upstream face, measured normal to the face of the dam, to accommodate all of the rock excavation from the spillway. The rock deterioration is not detrimental to the performance of the slope protection.
- b. At Black Butte Dam, the slope protection came from the basalt rock removed from the spillway excavation. The riprap broke down into smaller sizes than had been anticipated during design. As a result, wave action has formed benches in the riprap on the upstream slope where the pool has been at a relatively constant level for a period of time. Riprap thickness of 5 ft (measured normal to the face) has been sufficient to protect the face since 1963. Remedial work will be required if the wave action erodes through the slope protection.
- c. Slope protection riprap for major rolled earth-fill dams in the Sacramento District has come from spillway excavation or other required excavation. Slope protection has been provided in this manner for Terminus, Success, Isabella, Folsom, and Black Butte Dams. The material has performed satisfactorily.
- d. Slope protection for rock-fill dams consists of the rock-fill shell. New Melones rock fill came from the spillway excavation. New Hogan and Buchanan rock fill came from quarries opened up at the job sites specifically for those projects. The material has performed satisfactorily at all three sites.

- e. Slope protection for the Martis Creek rolled earth-fill dam came from a quarry opened at the job site initially, but the major portion came later from commercial sources. Those sources produced oversized rock from sand and gravel plant operations. The material has performed satisfactorily.
- f. Slope protection for minor dams that have no inactive storage has come from dredger-tailing cobbles. Slope protection for Farmington, Bear, and Mariposa Dams has been provided in this manner and has performed satisfactorily.

167. Slope protection for levees may present a somewhat different problem from protection for dams since the quality of rock is such a predominant concern in selection and performance. Sources of quality rock are not plentiful, so it is necessary often to use distant sources. Quality requirements are primarily based on performance record, petrographic examination, specific gravity, and absorption tests. The Los Angeles abrasion test is not considered reliable but may be included as a specification requirement at the option of the designers. The criteria for minimum bulk specific gravity and maximum absorption are based on experience with specific quarries and rock types. Where a satisfactory experience record is not available, the criteria and source evaluation are made more stringent.

168. The primary factor influencing the production of stone of the desired gradation is the geology of the quarry. Geologic evaluation of the parting planes, joints, and fractures in the rock is one of the first steps after the intrinsic quality has been established. Evaluations of quarry rock and operations are made by geology and materials personnel. Production methods influence the amount of waste and the attainable gradation. Systematic drilling and blasting, determined by experience in the quarry, are used almost exclusively.

169. Testing of samples from one quarry proposed for levee bank protection indicated borderline rock. The bulk specific gravity and absorption were marginal. The wetting-and-drying tests and the reported presence of montmorillonite also indicated marginal rock. High losses in the sulfate soundness test were not considered meaningful because the test discriminates against durable sandstones. Acceptance of

the source was based on the considerations that the quarry had been listed as an approved source, similar stone had a satisfactory 2-year experience record, and the source was the most economical. The limited performance period showed that the stone color was a convenient field indicator for separating durable stone from unsatisfactory stone.

170. Use of stone from this marginal quarry resulted in an inordinate amount of time expended in quality assurance and conferences at the management level. The right to reject unsatisfactory materials produced from localized areas or strata, provided by the project specifications, was used to obtain satisfactory rock. After the project was completed, it was deemed impractical to produce additional rock from the quarry. The quarry has been dropped from the list of approved sources. However, the selected rock has performed satisfactorily. The lesson learned was that marginal materials required considerable attention to quality assurance. When the quality assurance is provided, selection of better quality rock from the source may result in large quantities of waste. Therefore, a borderline or marginal quarry may not be economical.

San Francisco District

171. Riprap layer thickness for flood control projects generally ranges from 12 to 24 in. However, 8-in. layers of quarry spalls have been used for slope protection for highly erodible materials in low-velocity situations. In transition areas, where design velocities are usually higher, 24- to 36-in. riprap layers have been used as slope and invert protection. In locations with very high velocities, grouted riprap or concrete has been used. Slope protection is presently designed in accordance with EM 1110-2-1601 (Dept. of the Army, OCE, 1970), but prior to 1970, the criteria in EM 1110-2-3901 (Engineer Bulletin 52-15) was used. As a general rule, riprap layer thicknesses are increased 50 percent for underwater placement; and in areas subject to heavy floating debris, such as logs, layer thicknesses may be doubled. Typically, a riprap slope protection is placed on a 6-in. layer of filter-graded sand and gravel, but filter fabric has also been used.

172. Riprap is normally obtained from commercial quarries, and

sometimes from new quarries proposed by contractors if the rock meets durability criteria. Sandstone, glaucophane schist, greenstone, basalt, and dolomite are some of the rock types that have been used. This rock has specific gravities as high as 3.20 and has been very sound. Nearly all of the riprap is quarried and is very angular, but rounded cobbles have been used in certain locations. Stones up to 25 tons each have been used as armor units on jetties and breakwaters. Larger rock is usually difficult to produce, and shaped concrete units are more economical. Stones are barged or truck hauled as far as 300 miles to the project site.

173. Damage or failures are usually associated with toe scour, unravelling of downstream keys, disturbance by floating debris, and to a lesser extent by vandalism and the exceedance of design conditions. Problems have not been encountered in obtaining stone from commercial quarries.

Southwest Division

Albuquerque District*

174. Only occasional problems have been experienced by this District, as evidenced by the recognition of only one recent case of riprap deterioration. The sandstone used as riprap and spalls on Trinidad Dam had deteriorated to the extent of perhaps 10 to 15 percent in 1980 after 4 years and was expected to be in need of repair here and there in the intermediate future. This material was obtained from required excavation for railroad relocation. Suitable sandstone was present in the cut, but marginal to poor rock from adjacent strata was not effectively separated by the contractor as originally planned.

175. No laboratory testing was conducted because the Trinidad sandstone was judged to be clearly superior to shaly units above and below. The cementation of the inferior sandstone appears to be weak

* Information was obtained by telephone contact with District personnel, rather than by letter response to the questionnaire. The District is identified with others by a footnote in Table 2.

and to include some clay. The characteristic deterioration is by raveling or disaggregation of sand grains.

176. The contractor stockpiled the rock for a period of more than a year. Some deterioration took place during that interval, and the affected material was removed before placement. The District indicated that rock in the interiors of the 20- to 30-ft-tall stockpiles was probably protected and held temporarily in a stable state. Consequently, a mixture of acceptable and poor riprap stone, as yet unexposed to extended weathering, was loaded out for placement and the performance has been reflective of that mixture.

177. A major factor contributing to this problem is suggested to have been the formation of excessive blasting fractures during excavation. The permanent cut benches intended in the design are poorly preserved now as though fracturing was excessive. The District had attempted to cause a reduction in explosive loads without much success.

Fort Worth District*

178. This District has had no major concern with riprap in the past 10 years. Their single experience of stone deterioration, from 20 years ago, is included as an illustration of problems that still may arise in regions where stone is not plentiful. Stone for upstream slope protection on Sam Rayburn Dam had to be hauled about 150 miles by truck and railroad from a quarry near Palestine, Texas. The distance to a source would have been even greater except for the presence of domes at Palestine that exposed older, lithified strata normally found at depth. Stone at that time cost about \$1.50 per ton, but the cost has risen substantially since then. The Sabine River Authority built the Toledo project a few years later and chose soil cement as more cost-effective for upstream slope protection.

179. The Palestine rock was a quartzitic sandstone rated satisfactory by quality tests, including magnesium sulfate soundness, freeze-thaw, and wear tests. Despite the apparent suitability of the sandstone

* Information was obtained from District personnel by telephone, rather than by letter response to the questionnaire. This District is identified with others by footnote in Table 2.

as indicated by the tests, the riprap broke down appreciably in about 8 years. Hairline seams, not easily seen in the fresh rock, opened and, in extreme cases, were closely spaced in a laminar fashion. The seams were pyritic and apparently somewhat weathered.

180. Part of the problem seems to have been in sampling and in quarry evaluation. A visit was made to the quarry at the time the deterioration was first observed to be developing on the project. The quarry was supplying stone for another project, and there was concern that deterioration would follow to that project also. It was found that the quarry previously had produced from three faces. The variation in material from the separate faces was at the center of the problem. Riprap production from that quarry was subsequently restricted to only one face.

181. This District considers service records to be of particular importance in source evaluation. From such previous experience, not only on CE projects but also on other projects, it has been justifiable to use materials that would otherwise seem unsuitable. For example, one soft limestone giving borderline test results was known from service records to undergo beneficial case hardening after placement.

182. In amplification of question 4, the District recognized the common presence of poor zones in an otherwise good source quarry (e.g., see paragraph 180). This variation is more complicated than good and bad ledges or strata. For example, solutional activity in the Edwards Limestone has been seen to have developed vuggy zones of irregular configuration that are relatively poor in quality. Even where the openings are filled by deposition of secondary calcite, the suitability of the rock is reduced.

183. As a final comment, the District indicated a high regard for the results of petrographic analyses and considers them at least as important as results of quality tests.

Galveston District

184. Jetty stone used for construction during the past 10 years has not suffered a problem due to deterioration. The District regards experience records, quality test results, and cost as primary factors in

stone suitability, and pertinent physical specifications for armor and other stone are prepared accordingly. All of the stone used for riprap, armor, and jetty stone is furnished from commercial sources.

185. Stone in place since about 1880 has been inspected for weathering and other forms of deterioration. Samples were obtained and tested for magnesium sulfate soundness, Los Angeles abrasion, specific gravity, absorption, and unit weight. Comparison tests have been performed on stone from quarries that may be potential suppliers.

186. The District cites as an example of misleading test results a very hard, excellent quality granite that exhibits high (unfavorable) Los Angeles abrasion values. There are sources of limestone that contain both good and poor stone. The poorer stone tends to have lower specific gravity, higher absorption, and higher sulfate soundness loss.

Little Rock District

187. Significant to serious breakdown of riprap used on embankments in northern Arkansas and southern Missouri has resulted in overall reduction of the size of the stone fragments. The problem rock is dolomite containing featheredge shale partings and fractures, and the rock has broken down along these discontinuities. Deterioration appears to have been directly related to the frequency of inundation. Chief factors contributing to the breakdown were probably wetting and drying and freezing and thawing. Shale forming the partings may contain montmorillonite that would hasten the process.

188. Protection stone used along the Arkansas River is reported to have given good service. Rock types are sandstone, siltstone, limestone, and nepheline syenite. It should be noted that most of the protection stone used along the river has not been in service as long as the rock used at the large reservoirs, and its long-term resistance to deterioration is unknown.

189. The two major factors considered in selecting rock are quality and costs. The intent is to obtain satisfactory rock at the lowest possible cost. In most cases where satisfactory rock is available from more than one location, the chief factor is haul distance. Rock in northern Arkansas and southern Missouri was obtained from

Government land because it was less costly than similar rock from privately owned land.

190. Although tests for the dolomite described in paragraph 187 indicated satisfactory rock, the service record now indicates that the rock is not durable under the prevailing conditions. It should be noted that the rock was tested and evaluated for use as concrete aggregate rather than protection stone. The tests on relatively small pieces did not indicate the weaknesses along the discontinuities that are present in the large pieces used for riprap.

191. Rock from most quarries is not of uniform quality. Variations in lithology, weathering, and spacing of discontinuities are common, and good and poor quality rock may be found in the same source. In most cases, inferior rock is recognized as being of poorer quality, and only relatively small quantities are placed on a project. Almost all protection stone in recent years has been obtained from commercial quarries, quarries owned by contractors, or privately owned quarries operated by contractors.

Tulsa District*

192. The Tulsa District has had a definite problem with riprap used for slope protection. One case in point is Kaw Lake near Ponca City in northern Oklahoma. The original stone was 24-in. maximum size and was obtained from local commercial quarries operating within the Fort Riley and Herrington formations. The stone is hard, fine-grained limestone with numerous small fossils and occasional shale seams and has good to borderline durability according to testing and service records (see paragraph 73a for experience with Fort Riley Limestone in Kansas). Damage at Kaw Lake amounted to benching at the waterline caused by winter icing and subsequent removal of the stone by fluctuations in the pool level combined with wave action. Repairs were made during the winter of 1978-79 by replacing the original stone with 30-in. maximum size stone

* Information was obtained from District personnel during a visit to the project, rather than by letter response to the questionnaire. This District is identified with others by a footnote in Table 2.

from the Fort Riley formation. No further benching or deterioration has been noted through 1980. The icing problem has been experienced at other lakes across the northern portion of the Tulsa District. The stone is frozen in a thick layer of ice in the winter and upon partial thawing and breakup of the ice (coupled with a rise or fall of the water level plus the wave action), the stone is loosened or pulled out.

193. Another case is Clayton Lake, which was under construction in 1980 in southern Oklahoma. The stone for slope protection is from the Wapanuka Limestone near the base of Pennsylvanian strata along a resistant rock ridge located 32 miles from the dam. Two quarries, approximately one-half mile apart, have been operating along the uplifted edge of these strata for many years. The Carlton quarry has operated intermittently for special purpose stone such as riprap, while the Dolese Company quarry has operated continuously since 1966 as a large producer of crushed stone for all purposes, including riprap. The contractor initially proposed the Carlton quarry, and an investigation of its service records was made and complete testing was performed on representative samples from the exposed face. Test results indicated the stone to be hard and durable. Previous use as riprap on relocations projects appeared generally satisfactory after 17 years of exposure, although some deterioration and breakdown had occurred. After startup, the operator encountered some difficulty in production and proposed to purchase shot rock from the Dolese Company quarry. An investigation of this quarry revealed that the working face contained material similar to the stone in the Carlton quarry. Based on service records and previous testing of stone from this quarry, approval was given and production was started.

194. The Dolese Company quarry produces from several ledges that consist primarily of fine- to medium-grained, fossiliferous limestone with occasional stylolitic seams. The strata dip approximately 45 deg, so that the occurrence of ledges in the face varies with horizontal advance. Since the time of initial inspection and approval of the quarry, excavation has progressed 150 ft into the dipping strata and exposed a new ledge of hard, fine-grained limestone nodules embedded in a matrix

of argillaceous limestone at the top of the 80-ft vertical face. Some of this stone was placed on the slope about September 1979 and was not noticed as being of suspect quality until the spring of the following year. Considerable deterioration occurred during the severe winter. Another thorough investigation of the quarry was made and tests of the individual ledges were performed. Test results confirmed that some of the stone from the ledge of argillaceous limestone was indeed suspect (as indicated by the freeze-thaw tests). This material was immediately isolated in the quarry; however, most of the 24-in. riprap needed to complete the job was already in the quarry stockpile. An experienced geologist was assigned to monitor the selective loading of trucks to exclude the stone of suspect quality. Most ledges within this formation make very good riprap; however, selective quarrying and close surveillance by an experienced geologist is necessary to isolate ledges of questionable quality to prevent inclusion in production.

PART V: ANALYSIS OF EXPERIENCE

195. This part presents a synopsis of the experiences of the total CE community from responses to the list of questions in Table 1. Table 2 summarizes all responses of the CE Districts and Divisions.

Necessary Interpretation

196. Most of the responses from Districts and Divisions were in terms similar to those used in the original request, but some were narrative and thus required interpretation for uniformity of comparison and tabulation. Question 4 about stone from one source giving both good and bad service required the most interpretation. Respondents, perhaps keenly aware of variability in rock, answered "Yes" but went on to say that the poor quality stone was disapproved by quality control and acceptance inspectors and so was not placed in the projects. Therefore, since the stone was not placed in service, the interpreted answer was made to be "No."

Specific Questions

197. The following is a summary of the stated and interpreted views of all 38 District and Division offices that were contacted. Thirty-two of the offices responded first by letter, whereas the other six provided information by telephone or during field visits. The six responses by other than letter were somewhat distinct because of the opportunity to amplify on the questions and answers. It might be argued that the six should be excluded, and accordingly, they have been identified individually in Part IV and marked as a group in Table 2. Nevertheless, all responses are included in this analysis for completeness, also recognizing that the letter response varied in detail and emphasis.

Question 1

198. "Does deterioration or cracking of riprap, armor stone, jetty stone, etc., constitute an engineering, construction, or maintenance

problem in your District (Division) at present or in the past 10 years?"

The response was as follows:

<u>Answer</u>	<u>Number out of 38</u>
Never	14
Occasional	17
Significant	4
Serious	3

Question 2

199. "What are the major factors involved in rock selection and performance?" The response was as follows:

<u>Answer</u>	<u>Number out of 38</u>
Producer's capability and "interest"	14
Test results	25
Haul distance (to include method)	18
Fragment size, shape, and gradation	16
Cost	11
Past service records (specific source correlated with in-place performance and durability)	21
Accessibility	3
Project purpose and design	7
Ample sources available	8
Few sources available	7
Severe environment	8
Environment production restrictions	3

Of the 25 respondents identifying "Test results" as a major factor, only 11 specified particular tests, as follows:

<u>Test</u>	<u>Number</u>	<u>of 11</u>
CRD-C 107 Specific gravity	6	
CRD-C 127 Petrographic examination	4	
CRD-C 137 Magnesium sulfate soundness	3	

(Continued)

<u>Test</u>	<u>Number out of 11</u>
CRD-C 145 Los Angeles abrasion	3
CRD-C 107 Absorption	3
CRD-C 144 Freeze-thaw cycling	4
-- Wet-dry cycling	2
CRD-C 107 Unit weight	2
-- Hardness	2
CRD-C 148 Ethylene glycol	3

The implied importance of the specific gravity is somewhat exaggerated in the context of rock quality since specific gravity is determined partly for use in hydraulic designs.

Question 3

200. "Are there cases where testing has indicated marginal or poor stone quality, but service after placement has been satisfactory or vice versa?" The response was as follows:

<u>Answer</u>	<u>Number out of 38</u>
No	15
Yes	23

The 23 "Yes" answers gave sufficient information for subdivision into the following two possibilities:

<u>Answer</u>	<u>Number out of 23</u>
Satisfactory test results followed by poor service	14
Poor or marginal test results followed by satisfactory service	15

Six Districts have had both experiences.

Question 4

201. "Are there cases where the stone from one source has given both good and bad service?" The 37 offices that responded to this question indicated:

<u>Answer</u>	<u>Number out of 37</u>
Yes	15
No	22

The 22 "No" answers include 10 that stated explicitly that heterogeneity occurred, but poor rock was not accepted or used.

Question 5

202. "What are the types of sources of riprap, armor stone, jetty stone, etc., in your District (Division) in recent years?" The 37 offices that responded to the question indicated their common source or sources as:

<u>Answer</u>	<u>Number out of 37</u>
Commercial quarries	36
Required excavation	16
Onsite (Government-owned) quarries	7
Concrete (broken paving or manufactured units)	4

Answer Correlations

203. Further analysis of the 38 responses from the individual Districts and Divisions has led to several correlations.

Test results

204. Of the 25 responses explicitly identifying "Test results" as a major factor in the selection and performance, there were 7 that also stated they had "No" problems with stone deterioration and 12 others that had "Occasional" problems. These same 25 responses also included 17 statements that described cases where analyses of test results predicted stone performance that differed from actual experience. The experiences of good test results but poor service and poor test results but good service were reported equally. In studying the responses further, it is apparent that many such cases simply involved the testing of unrepresentative samples. The same 25 offices citing "Test results" can be divided into 13 where single sources provided stone that showed consistent service performance and 12 where single sources provided stone

that varied in performance. Again, the latter experience seems to reflect the common existence of areas or ledges of poor stone in otherwise suitable quarries and the attendant complications in representative sampling.

Districts (Divisions)
without problems

205. Fourteen offices stated they had "No" problems with stone deterioration. Eight of those fourteen stated there were no cases where test results disagreed with observed performance. Five of the other six offices reported cases of poor test indications disagreeing with satisfactory service, and two reported cases of the opposite combination. Twelve of the offices that had "No" problems at all with stone deterioration also said there were no variations in service performance of stone from individual sources.

Districts (Divisions) with problems

206. Seventeen offices described their stone protection problems as "Occasional" or stated only a single instance in a decade. Seven of those seventeen said they recognized no circumstances of test results disagreeing with service performances. Eight referred to tests indicating poor or marginal stone, in contrast to the satisfactory performance actually realized. Seven respondents described the opposite situation. Finally, 10 of the 17 offices recognized no occurrences of variability in service performance of stone from a single source.

207. Seven of the offices described their stone deterioration problems as "Significant" or "Serious." All of these found discrepancies between test results and service performance. Two of the seven identified the situation of poor or marginal test results despite satisfactory service performance while five chose the opposite possibility. All seven offices citing "Significant" or "Serious" problems answered "Yes" to the question about occurrences of single-source rock giving both good and poor service.

Geographic distribution

208. It is revealing to make one geographic correlation, based on the locations of the Engineer Divisions. Seventeen of the twenty

offices in the Divisions (New England, North Atlantic, North Central, Ohio River, Missouri River, and North Pacific) that can be characterized as encompassing the northern regions indicated "Occasional" to "Serious" problems. Two of the three exceptions citing no problems have considerable project work in middle to southern areas. Eleven of the eighteen offices in the other Divisions (South Atlantic, Lower Mississippi Valley, Southwest, South Pacific, and Pacific Ocean) characterized as southern regions indicated no problems. Six of the other seven offices indicated "Occasional" problems while only one cited "Serious" problems. Accordingly, it is somewhat surprising that just five out of the eight offices quoting "Severe environment" as a factor are in the northern regions.

209. The factors considered important to stone selection and performance show little geographic correlation except that most Districts (Divisions) quoting "Ample sources" are in the northern regions.

PART VI: CONCEPTS OF ROCK SLOPE PROTECTION

210. Anticipating the performance of riprap or armor blanket material can be quite complicated since it involves other factors as well as material behavior or properties. All factors that enter into a comprehensive evaluation are recapitulated in this part. A brief explanation is given on how each factor may have to be considered before specific evaluations of one rock source versus another can be made. Some of these diverse factors were brought out in the Corps-wide questionnaire response (see Parts IV and V). Others were identified in the course of discussions with personnel at selected District offices. In addition there are other factors that were not identified in the survey of CE experience but which have been deduced from a review of the concepts and processes involved.

Material Suitability

211. Two aspects of suitability of rock materials for slope protection layers clearly distinguished by CE experience are: the suitability of the intact rock, and the arrangement and nature of rock mass weaknesses such as joints.

Intact rock

212. In the course of this study, an attempt has been made to identify certain ranges of suitability predictable on the basis of simple geological rock type, an ambitious and in some cases unrealistic goal. The logical previous study on which to build was that of the Bureau of Reclamation in which failed rock slope protection was identified from bureau-wide experience. Pertinent results of that study are shown in Table 3 in a highly simplified form. Only the failures involving rock deterioration as opposed to design considerations were included in the table. Since that previous work did not indicate a strong tendency for failures caused by rock deterioration to be associated with generally weaker rocks, a review of this subject based on CE experience seemed appropriate. It was recognized that considerable subjectivity and judgment necessarily exercised.

213. On the basis of CE experience and with cognizance of rock properties, environment, and other characteristics and factors, the following generic series seems to approximate best to poorest field durability.

- a. Granite.
- b. Quartzite.
- c. Basalt.
- d. Limestone and dolomite.
- e. Rhyolite and dacite.
- f. Andesite.
- g. Sandstone.
- h. Breccia and conglomerate.

It has to be emphasized and reemphasized, however, that such general guidance should not be overextended. Experience with basalt is a good case in point. Some experience of the North Pacific Division indicates that basalt performs poorly (see paragraphs 114 and 128); but elsewhere in the Division some of the best large stone is basalt (see paragraph 120). Many exceptions to the ranking above will be found, and beyond preliminary generalizations, test results and past performance records should be the determining factors.

Field data and quarry examinations

214. Rock mass weaknesses such as joints can have considerable importance in riprap and armor since they often determine the ultimate size of stones. In addition, poorly developed or incipient joints can contribute to a continued deterioration of stones from a previously intact condition. The review of CE experience has suggested that careful examination of the quarry face has usually been sufficient to forewarn of problems of this nature or of limitations on riprap stone size and gradation. It is also evident that representative sampling is essential to avoid the unintended use of some inferior material present in a quarry but not sampled.

215. Evaluation of quarry faces has not always been routinely accomplished in the CE. Obtaining such a data base now would be an immense undertaking. Quarry inspection reports are available here and

there; but many quarries, especially the older ones not used recently, are not well documented. New quarry inspections have become a matter of routine in some Districts. Such inspections should include special effort to identify individual layers or less regular zones with separate intact or jointing characteristics. Some rather general simplifications on joint spacing are highly useful in predicting size and gradation of the riprap product. Districts that routinely inspect quarries maintain up-to-date files of such quarry reports and are in a position to supplement these files of information by exchange and sharing with adjacent Districts as needed.

Available Materials and Performance Life

216. When a riprap blanket is designed, an expected life before replacement is usually not defined. A few tens of years without repair seems to be the longevity considered as adequate. The reasons why eventual deterioration and the need for repair do not cause more concern than they do are the low hazard potential of such degradation (in most but not all cases) and the prevailing situation wherein the slope protection blanket becomes the responsibility of an operations organization after construction. Funds are available for maintenance and repair, and the operations organization commonly maintains a stockpile of rock for any repairs that are needed. The deterioration of riprap usually develops over a period of time sufficiently long that needed repairs can be worked into the maintenance schedule, well short of an emergency basis.

217. A closely related question in constructing slope protection is whether to use readily available and inexpensive rock from required excavation. Such stone will generally be inferior to stone obtained specifically for riprap and armor. However, this study has indicated that CE Districts commonly choose to use required excavation rock in place of more costly contracted or purchased rock. Once this concept is understood and appreciated, considerable confusion about the existence of problems with riprap stone disappears. Thus, a District may judge that it has had no problem with riprap deterioration because a

certain amount of deterioration was anticipated when it was decided to use a relatively inexpensive rock.

218. A case in point is the upstream slope protection at Milford Dam, Kansas (U. S. Army Engineer District, Kansas City, 1964). The material was limestone from a quarry upstream along the dam abutment, somewhat lower in unit weight and higher in absorption than would be preferred (see paragraph 73a). Quarry-run rock was used because of the availability of the local stone. Removal of fines was accomplished at the quarry by using a slotted bucket. Some small sizes remained, and some weathering breakdown was expected to reduce the average size even further. The District therefore compensated for this shortcoming by specifying a riprap thickness somewhat greater than ordinarily prescribed according to EM 1110-2-2300 (Dept. of the Army, OCE, 1971b).

Constraints on Choice of Quarry Source

219. Certain factors principally involving economics and profit enter into the determination of what source will supply riprap or armor. Some quarrymen contacted in this study complained of their problems in meeting new and different gradation requirements on each new project. In such cases, quarry managers expressed the strong opinion that the use of only a relatively few gradations would be highly beneficial to their planning and, in turn, would result in cost savings to the project. This concept deserves careful review from the CE point of view to determine whether any standardization is possible.

220. The CE has had varied degrees of success with the concept of a "list" of quarries from which the contractor may choose his source. In this arrangement, certain quarries achieve an elevated status on the basis of laboratory tests and service records of their product. This basis for evaluation can fall short if there is considerable variability in vertical and lateral directions within the quarry. The North Central Division has discontinued the use of lists of approved quarries as sources for large stone for dike construction. A list of sources is still provided for consideration by the contractor.

221. As another safeguard, it is considered appropriate to update the file on proposed quarries by requiring new test programs. A quarry thus remains subject to reevaluation. Over a period of time such files can accumulate and become increasingly more valuable, since they will tend to reveal the regularity or variability of rock within a source.

222. Other important constraints that bear on the choice of a quarry are the distance and type of required transportation, factors that translate directly into cost. When only one mode of transportation is involved, the job of evaluating this factor is relatively simple. A certain freight charge per mile favors nearby sources more or less proportionally to the distance from the source to the project. Simply stated, it is reasonable to expect that the nearby quarry of a group of similar quarries will have a decisive advantage; i.e., transportation costs are significant to that great a degree.

223. Transportation that involves more than one mode complicates the estimation of transportation costs. Ordinarily, an estimator might expect barge transportation to be cheapest followed in order by rail and truck. However, each loading, transferring, and unloading operation adds an increment to the cost. Even so, contractors will occasionally find it advantageous to choose another combination rather than that indicated in the Government's estimation. For example, a construction contractor conceivably might own or lease and operate a quarry at some distance (at higher transportation cost) in order to keep his equipment and employees from periods of idleness. The Fisher quarry (see paragraphs 37 and 120) illustrates the ultimate, though not necessarily decisive, combination. This important jetty stone source located on the Columbia River is owned by a construction company with barge transportation capability. The firm has often bid low on jetty repair jobs along the Oregon coast.

Contract and Construction Procedures

224. One particularly critical part of construction is the preparation of the specifications and plans. The current philosophy is to use previous terminology and specifications (or guide specifications) that

have been found to be tried and true. Such terminology tends to fall midway between directions that are qualitative and those that are quantitative. The qualitative instructions that tend to describe the results to be achieved depend on the resident engineer exercising his judgment and authority on the construction job. The quantitative-type specifications have been found to be effective and dependable from the Contracting Officer's point of view only through experience from many previous jobs. The quantitative-type specifications may also place greater emphasis on acceptance testing of randomly selected samples from deliveries to the job site that, in turn, relies on the effectiveness of the quality control program. Also, a limited effort has been made to influence the quarrying methods of the stone supplier by wording in the contract; however, most Districts have avoided any such complicating involvement in the past.

225. Material conditions and placement of riprap and armor stone depend heavily on the quality control-quality assurance system for success. This system in turn seems to work best when a written report of conditions and progress on the job is prepared regularly. There are, of course, limitations on what can be accomplished or formalized in specifications regarding riprap slope protection. Slope protection usually constitutes only a small part of a contract, and pertinent provisions tend to be short and concise. Specifications for breakwater, jetty, or dike armor can be more comprehensive since these features constitute a major part of the total project.

226. This study has indicated that some special precautions may be warranted in the specifications or at least should be brought to the attention of the resident engineer. Local CE experience suggests that quarrying in the winter in northern and central regions may produce inferior riprap and armor. Some specifications discourage or prohibit the use of such stone (see paragraphs 98 and 100). There is also a popular viewpoint that special blasting techniques are needed to produce durable stone (see paragraphs 115 and 177). This belief locally clashes with the common practice among commercial quarries supplying large stone from oversize material in crushed stone operations.

227. The construction contractor may influence the performance of protection stone indirectly, as well as directly (by the choice of the stone source). He has the responsibility for determining the equipment to be used in construction from possibilities as diverse as placement with hydraulic handlers positioned on the slope or dike and placement with a crane mounted on a barge. Among placement procedures causing concern is the passing of tracked vehicles over stone in place (see paragraph 135) or any extra handling (see paragraph 149) with attendant breakdown and production of fines.

PART VII: CONCLUSIONS AND RECOMMENDATIONS

Conclusions

228. This report has defined and described problems with riprap and armor slope protection and identified aspects needing further study. Guidance has been provided for avoiding in the future many problems that have occurred in the past. Previous literature and other guidance on the subject are scarce so this summary and critical review has also served usefully to document the current state of the technology.

229. Salient conclusions of this report are as follows:

- a. Stone deterioration continues to occur now and then in about half the CE Districts. Most problems have been minor, but a few have been significant to serious.
- b. Six modes of rock deterioration can be distinguished: cracking, spalling, delaminating, disaggregating, disintegrating, and dissolving. Such distinctions should be sought in an endeavor to identify the cause of deterioration.
- c. Many factors influence deterioration besides the characteristics of the intact rock. Therefore, a rating of durability by rock type is difficult to obtain in an objective manner. This study has suggested a general order of rock suitability that should be useful in a preliminary way despite its subjective basis.
- d. Certain tests that have been more or less standardized are widely accepted and used for evaluating stone as riprap and armor. These tests are adapted or have evolved from those used extensively for concrete aggregate. The tests explore in a simplified way the resistance of the rock to abrasion, freeze-thaw, and wet-dry environmental attack. The wide acceptance provides a useful frame of reference for comparing test results. However, even when appearing to be clear and straightforward, the results are sometimes misleading in predicting protection stone performance.
- e. A standard procedure for a wetting-and-drying test is needed, and a proposed procedure is included in this report.
- f. Modification and standardization of other tests should be considered also. This study and previous efforts have indicated that the freezing-and-thawing test is more

representative when conducted using large test pieces (e.g., 1 ton for armor stone).

- g. Although the experiences of several Districts indicate that better tests are needed, attempts at developing such tests have not been particularly successful as judged from low acceptance and usage.
- h. In some cases, the field evaluation of the rock source is more important than testing. Important limitations imposed by natural jointing and variations of bedding are included in this manner.
- i. The field examination should also support the testing by estimating how much of the quarry is represented by each of the samples to be tested. Boundaries between sampled types should be delineated.
- j. Economic considerations commonly impact on engineering considerations. Some slope protection has been constructed using required excavation rock with the understanding that the rock was of lower quality than rock purchased from an outside quarry source. Sixteen of the offices contacted indicated this type source in common use. Sometimes the design of protection was modified to compensate for these shortcomings in rock quality. Results were mostly satisfactory and about as expected.
- k. It follows from the philosophy stated in j that continuing maintenance and maintenance cost (for riprap) should be recognized in the planning stage and perhaps identified in the project life-cycle cost. It may be that use of the poorer material is the best economic choice, but on the other hand it may not be because of the present inability to predict accurately the optimum interval for maintenance.
- l. Quarrying methods (particularly blasting) must be carefully considered in regard to stone quality, average size, and size gradation. Some quarry operators see potential for cost reduction if the CE can use only a relatively few standardized size gradations.
- m. Construction methods can also affect the performance of the stone protection system. Most of the potential for improvements here falls nearest the area of responsibility of the Construction Division (in Districts) but more specifically rests with the contractor.
- n. Regardless of the quality of the rock, a key part of any riprap or armor project is the quality control-quality assurance program and its effectiveness.

230. Individual problems arising with the use of large stone

materials as protection on banks, channels, and embankments or on dikes, jetties, and breakwaters are not of Corps-wide magnitude. Almost half the offices contacted reported there have been no problems in the last 10 years. However, it would be understating the actual situation to describe problems as only local. Continuing study aimed at improved stone performance and service seems warranted.

Recommendations

231. Subjects for further study fall into two groups, testing-related problems and geotechnical problems.* This study tends to indicate potential for improvements in both subject groups, with objectives in the first group as follows:

- a. Checking and modifying, as necessary, current tests for evaluating large stone material (in sizes larger than those for aggregate).
- b. Exploring new test methods such as adsorption-absorption and ultrasonic disaggregation.
- c. Reviewing the applicability of less favored tests (Los Angeles abrasion and sulfate soundness).

The several Division Laboratories are positioned advantageously for these objectives by virtue of their experiences, observations, and continuing involvement.

232. Likely improvements of a geotechnical nature are indicated as follows:

- a. Developing field procedures for describing and sampling quarries and other sources of stone.
- b. Reviewing quarrying and excavating techniques and construction methods for significant effects on stone performance.
- c. Preparing portions of guide specifications on stone sources, quarrying, placement, and quality control-quality assurance to accommodate the findings of this study.

* The two-fold division was specifically requested by the sponsor to distinguish improvements needed in laboratory techniques from problems within the responsibilities of Geotechnical Branch personnel.

These latter objectives should be pursued by or through the Geotechnical Branch (Foundation and Materials Branch) of the individual Districts (Divisions).

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Table 1
Questions for Consideration by CE Offices on Experience
with Riprap, Armor Stone, and Jetty Stone

1. Does deterioration or cracking of riprap, armor stone, jetty stone, etc., constitute an engineering, construction, or maintenance problem in your District (Division) at present or in the past 10 years? (For example: never, occasionally, significantly, seriously, etc.; and if so, explain to the degree possible)
 2. What are the major factors involved in rock selection and performance? (For example: severe environment, plentiful sources, source distance, contractor procedures, high cost, quarrying and handling, etc.; and explain to the degree possible)
 3. Are there cases where testing has indicated marginal or poor stone quality, but service after placement has been satisfactory or vice versa?
 4. Are there cases where the stone from one source has given both good and bad service? If so, explain.
 5. What are the types of sources of riprap, armor stone, jetty stone, etc., in your Division in recent years? (For example: commercial quarries, Government quarries, required excavation; and explain to the degree possible)
-

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ARMY ENGINEER WATERWAYS EXPERIMENT STATION VICKSBURG--ETC F/6 13/3
EVALUATION OF QUALITY AND PERFORMANCE OF STONE AS RIPRAP OR ARM--ETC(U)
SEP 81 R J LUTTON; B J HOUSTON; J B WARRINER

UNCLASSIFIED

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Summary of Responses from Districts and Divisions

[illegible]

* Data from other than letter response.

Table 3
Bureau of Reclamation Experience with
Service from Rock Types*

<u>Rock Type</u>	<u>Description</u>
Granite and granite-type	Recommended
Limestone	Next most successful (after granite)
Sandstone	Next most successful (following limestone closely)
Basalt	Most troublesome

* From Esmiol (1968).

APPENDIX A: INVESTIGATION OF IMPROVEMENT IN FREEZE-THAW
TESTING BY USE OF LARGE BLOCKS

1. Previous testing of stone for armor (particularly at ORDL) has indicated that using 2-in.-thick slabs makes a significant improvement in freeze-thaw test results. Large blocks are even more likely to contain defects present in the armor stone and also to respond in a realistic manner to the simulated freeze-thaw environment. This appendix explores the size effect between 2-in. slabs and full blocks using a stone type known to have experienced considerable cracking in service.

Rock Types and Samples

2. The two rock types tested in this study were a dolomite with a record (on one project) of serious cracking deterioration and an igneous rock with an excellent service record. Samples of the igneous rock (a syenite from Sweet Home, Arkansas) served only for test control; therefore, their behavior under testing is of only secondary interest.

3. The dolomite is Silurian in age and was obtained from a quarry near Sussex, Wisconsin. Armor stone from this quarry was placed on the dike for the confined dredge disposal area at Milwaukee Harbor, Wisconsin. The stone was transported to the project by truck. District personnel reported that the stone appeared sound when it arrived at the construction site, but a few stones began cracking upon dumping from the trucks. Severe cracking began a short time after the placement was completed, probably after a few cycles of freezing and thawing (see paragraphs 17-20 and 99 for a summary of the problem).

4. At the time of sampling on the dike, 5 years after construction, riprap-size (smaller) stone appeared to be in good condition except for isolated particles that had broken down. However, the larger stone of armor size experienced moderate to severe cracking, from single to multiple cracks and from tight to open cracks. Most of the cracks are normal to bedding; a few are parallel to bedding.

5. Two samples of dolomite were obtained in the field and shipped

to the laboratory for testing. One stone (CL-31G-2) weighing about 2600 lb was selected in the quarry. The other sample (CL-31G-1) measuring 1.0 v 1.4 v 0.2 ft was obtained on the dike. This sample from the disposal area had been exposed on the dike for approximately 5 years where it had separated along a break from a piece of armor stone. The stone was a homogeneous, fine-grained, pure dolomite rock.

6. The syenite stone (sample CL-31G-3) obtained from the quarry in Arkansas weighed approximately 1 ton. A fourth sample (NO-57G-78) was prepared from the same syenite quarry rock already on hand in the laboratory from another project.

Slab Tests

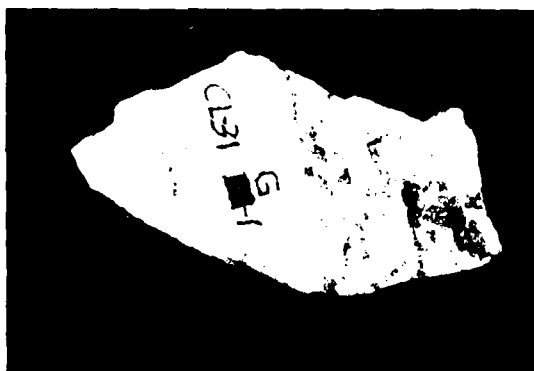
7. A 2-in. slab was cut from each of the two large stones (CL-31G-2 and CL-31G-3). The slab of dolomite was oriented perpendicular to the bedding planes. All slabs were tested according to method CRD-C 144 (U. S. Army Engineer Waterways Experiment Station 1949b). Figure A1 shows the slabs before and after testing. Slab CL-31G-2 broke along a bedding plane while being sawed.

8. The following are the results of the freezing-and-thawing tests of the sawed slabs according to method CRD-C 144. The test on CL-31G-3 was carried only to 12 cycles and thus was incomplete. All results indicated acceptable stone.

<u>Sample No.</u>	<u>Rock</u>	<u>Cycles</u>	<u>Percent Loss</u>	<u>Remarks</u>
CL-31G-1	Dolomite	20	1.0	Riprap-size slab
CL-31G-2	Dolomite	20	0.6	Larger slab
CL-31G-3	Syenite	12	0.0	Large slab
NO-57G-78	Syenite	20	0.0	Riprap-size slab

Block Tests

9. The principal effort reported in this appendix is the testing of full blocks of stone (Figure A2). The slab tests summarized above were only for comparison. The two blocks were ready for testing at the



Before



After

Dolomite CL-31G-1



Before



After

Dolomite CL-31G-2



Before



After

Syenite NO-57G-78

Figure A1. Results of freezing-and-thawing test CRD-C 144



Figure A2. Syenite instrumented with thermocouples

laboratory by June 1980 and the preparation and testing were continued through June and July.

10. The two large stones (after removal of one slab from each) were instrumented with thermocouples, at 2-in. depth intervals to the center, to determine when the stone was frozen or thawed completely. The stones were then submerged in a water solution containing 0.5 percent caprylic alcohol in a tank as shown in Figure A3 (note the thermocouple leads). The tanks were placed in a controlled temperature room at $-15 \pm 3^\circ\text{F}$ for freezing (Figure A4) and then were removed and thawed outside the laboratory. The outside daily high temperature was about $90^\circ\text{-}100^\circ\text{F}$. The time required for freezing the large stones was more than 6 days while the thawing took about 2 days. The complete 16-day time history of temperature in the dolomite block during cycle 1 is shown in Figure A5 for the thermocouples near the surface and at depth. Thermocouples at 5- and 9-in. depths tended to give records between these extremes.

11. The freeze-thaw cycling of the full blocks was somewhat limited because of recurrence of equipment problems. After three cycles of freezing and thawing, the syenite (CL-31G-3) showed no sign of deterioration. After five cycles, the dolomite (CL-31G-2) exhibited what appeared



Figure A3. Loading syenite stone for testing

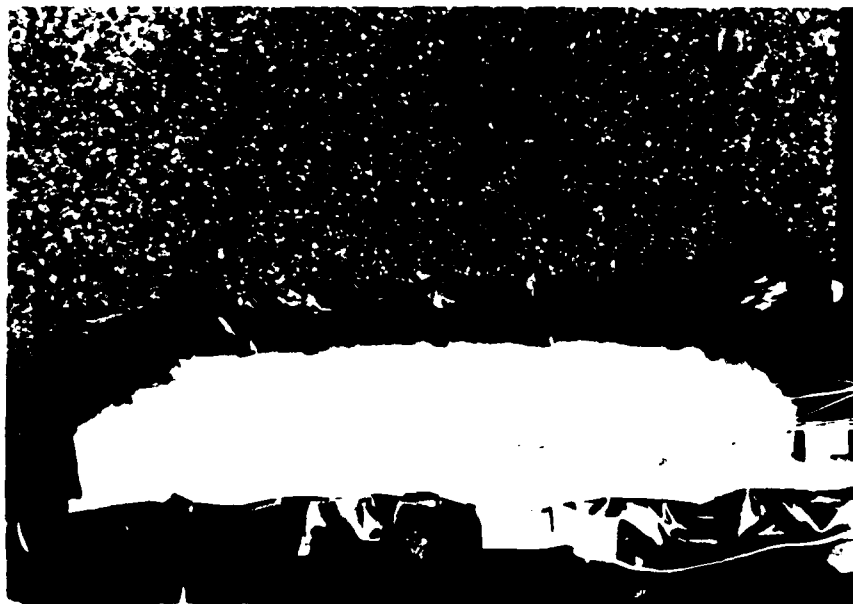


Figure A4. Frozen solution enclosing
instrumented stone

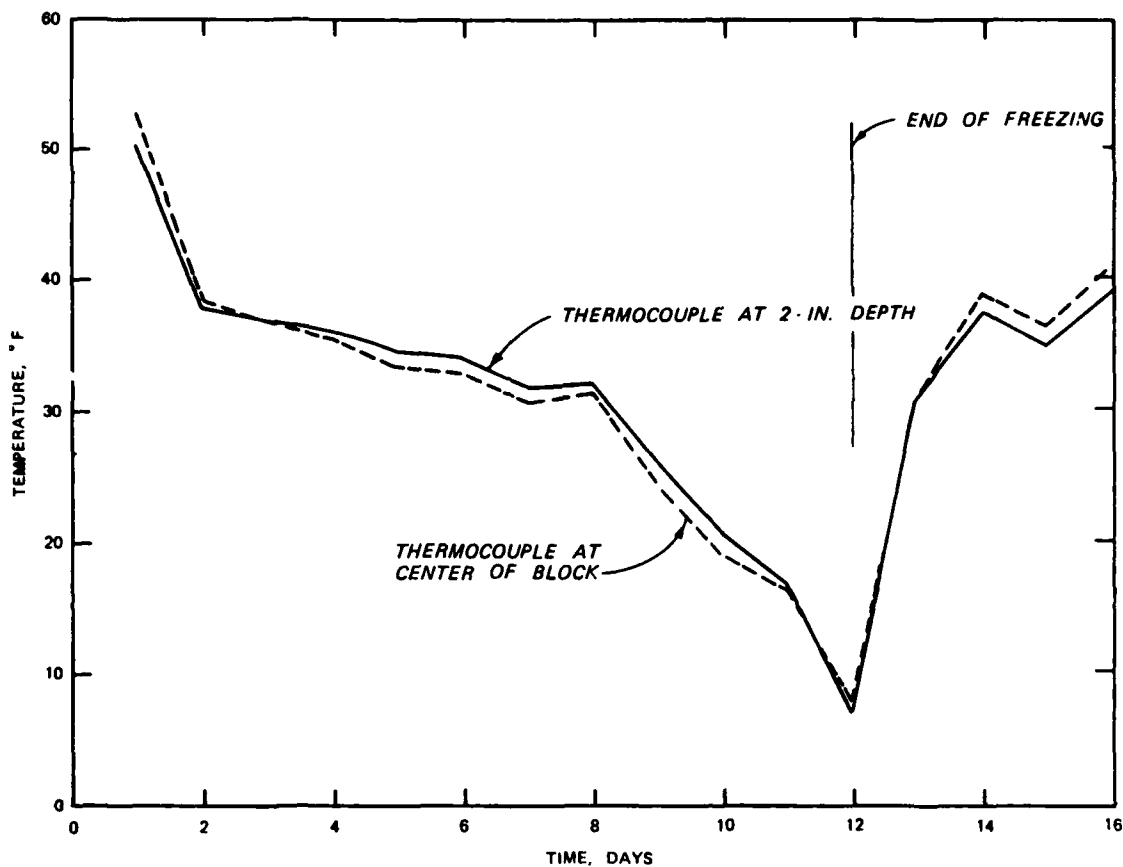


Figure A5. Cycle 1 of freezing and thawing of dolomite stone

to be deep cracking. The test results, cycle by cycle, were as follows for the dolomite.

<u>Sample</u>	<u>Rock</u>	<u>Cycle No.</u>	<u>Condition</u>
CL-31G-2	Dolomite	1	No cracking
		2	No cracking
		3	Minor cracking
		4	Moderate cracking
		5	Moderate cracking

Figure A6 shows the condition of the dolomite stone during the test period, including the developing cracks.



Figure A6. Dolomite block after five cycles with crack at lower left developed by testing

Discussion of Test Results

12. Special freeze-thaw testing using large blocks has provided evidence that appears to confirm the importance of size effects in testing rock for riprap and armor stone. Samples of rock with good or bad service records were indicated to be of satisfactory material when tested according to standard method CRD-C 144 on slabs. On the other hand, the special freeze-thaw tests on blocks weighing about 1 ton seem to have distinguished the poor and excellent stone types. Accordingly, the use of large block samples may be a significant improvement in technique in freeze-thaw testing provided the special equipment and additional time and expense are not too restrictive.

APPENDIX B: PROPOSED STANDARDIZATION OF TEST METHOD OF TESTING
STONE FOR RESISTANCE TO WETTING AND DRYING

Scope

1. This method covers a procedure for determining the resistance of stone to wetting and drying. Information developed by use of this method may be applicable in the evaluation of stone for use as slope protection, as concrete aggregate, or for other purposes.

Apparatus

2. The apparatus shall consist of the following:

- a. Saw. A rock-cutting saw, preferably having a diamond blade, of suitable diameter for sawing specimens.
- b. Pans. One or more pans, each large enough to hold one sample slab, with sides at least 3 in. high, made of stainless steel or other suitable noncorroding material.
- c. Specimen supports. Specimen supports to hold specimens above the bottom of the pan shall consist of lengths of noncorroding material approximately 1/4 in. in diameter.
- d. Drying oven. A drying oven, as described in CRD-C 137 (U. S. Army Engineer Waterways Experiment Station 1949b), of sufficient capacity for containing the samples in the pans.
- e. Balances or scales. Balances or scales having a capacity adequate for weighing the test material to an accuracy of at least 0.1 percent of the weight of the material being weighed.
- f. Photographic equipment. Equipment suitable for preparing photographs of the test samples before, during, and after test.

Test Specimens

3. Specimens for use in this test shall be sawed slabs $1 \pm 1/4$ in. thick. Specimens shall be prepared to represent each of the principal varieties and conditions of rock present in the sample. Selection of material to use in preparation of specimens shall preferably be

accomplished using the procedures described in CRD-C 127 (U. S. Army Engineer Waterways Experiment Station 1949b).

4. Slabs should be sawed so as to include at their edges as much of the surface of the material received for testing as possible. Slabs from rock having visible bedding planes or other planar structures should usually be prepared by sawing normal to such structures. Preferably three specimens should be prepared to represent each principal variety or condition of rock. Slabs should be as large as the material available for their preparation will allow, up to the capacity of the pans used for the test (see paragraph 2b).

5. Slabs of different materials, the performance of which is to be compared, should preferably be of similar sizes.

6. Slabs prepared with sawing equipment and cutting oils shall be carefully cleaned of oil by use of suitable solvents. After having been sawed and cleaned, slabs should be inspected by the same procedures that were employed in selecting material from which the slabs were sawed to confirm that the slabs adequately represent the types and conditions of material that were intended to be represented. In the event that a sawed slab is found to be nonrepresentative, additional material should be selected and a replacement slab prepared that is representative.

Procedure

7. After having been cleaned of cutting oil, each test specimen shall be examined and preferably photographed.

8. One test specimen shall be placed in a pan and covered by water so that the depth of the solution over the upper surface of the specimen is $3/4 \pm 1/4$ in. The total volume of a test specimen placed in any one pan shall be such that the volume of rock does not exceed the volume of the solution.

9. The pans containing the specimens shall be stored at $73 \pm 3^{\circ}\text{F}$ for at least $16 \pm 1/2$ hr. They shall then be removed from water and placed in the oven for $8 \pm 1/2$ hr at $180 \pm 5^{\circ}\text{F}$. Afterwards, they are removed and inspected to observe the effects of the exposure. Any observed

changes should be recorded, and the specimens should be photographed if these changes are regarded as significant.

10. Additional cycles of wetting and drying, followed by inspection and photographing as may be appropriate, shall be continued until a total of 30 cycles has been obtained. The water shall be maintained at the specified depth by adding additional water as needed. After every 5 cycles, the water shall be carefully poured off through a No. 200 sieve so as not to displace any of the fragments of the samples; any material caught on the sieve shall be returned to the pan. New water shall then be added. When a 16-hr or 8-hr cycle is interrupted, as for holidays and weekends, the specimens shall remain in a dry condition until the sequence is resumed.

11. The exposure of a specimen may be terminated prior to completion of 30 cycles if the largest remaining fragment of the slab amounts to less than half of the original specimen.

12. After the wetting-and-drying cycle has been completed, the water shall be carefully poured off using the procedure described in paragraph 10. Then the contents of the pan, both that remaining in the pan and the material caught on the No. 200 sieve, shall be dried in the drying oven until the loss in weight between successive weighings at intervals of not less than 4 hr does not exceed 0.1 percent of the later weight. The dry weight shall be recorded. The dry weight of the pan and contents, less the weight of the pan, will be taken as the initial dry weight of the specimen. The contents of the pan should be photographed. Each fragment weighing more than 25 percent of the initial dry weight of the specimen shall be weighed, and the sum of the weights of such fragments shall be recorded.

Calculation and Report

13. The report shall include the following:

- a. Source of material.
- b. Tabulation of data on each test specimen as follows:
 - (1) Designation of type and condition of rock represented.

- (2) Initial dry weight (obtained as described in paragraph 12).
- (3) Changes observed at each inspection.
- (4) Number and weight of all fragments remaining at conclusion of test that weigh more than 25 percent of the initial dry weight of specimen.

c. Photographs as appropriate.

Results

14. Results of this and other tests on riprap will be reported to the using agency without any interpretation of results by the laboratory.

Interpretation

15. The results of this test should generally be employed as a basis for comparing the relative resistance of different types of material, from one or more sources, being considered for the same use. The results of this test as performed on a single material will not ordinarily provide a basis for concluding that the material is "satisfactory" or "unsatisfactory" for a proposed use unless the specimens are essentially completely either unaffected or disintegrated by the action of the test. The interpretation of the results will also depend on the nature of the material tested, the degree to which the specimens represent the material, and the intended use (see paragraphs 16 and 17).

16. Rock of uniform structure and texture intended for use as a source of either protection stone or crushed stone for concrete aggregate will generally be affected by surface scaling, crumbling, flaking, or disaggregation. The total amount of material separated from the largest remaining fragment, i.e. the weight loss, will normally be a suitable basis for quantitative comparison of such materials.

17. Rock with observable bedding planes, joints, seams, stringers, or other planar structures will generally be affected, if at all, by separation into discrete portions along such planes. Such separation may be of little importance when the rock is being considered as crushed

stone aggregate to be confined in concrete. Such separation may be of much greater importance in rock proposed for use as protection stone. In the latter instance, however, it will be necessary to estimate the separation distance of the planes such as those at which test specimens have separated in the material from which the specimens were made. If these planes are so closely spaced that the stone, after separating thereon, is in sizes too small to serve the intended purpose, the rock may be unsuitable for such use. If these planes are more widely spaced, or only infrequently closely spaced, the rock may be suitable for such use, even though planes of potential separation are present.

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